Physics-Based Virtual Fly-outs of Projectiles on Supercomputers

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ABSTRACT

This paper describes the development and application of a new multidisciplinary computational capability to compute the flight trajectories and the free flight aerodynamics of projectiles. Advanced computational capabilities both in computational fluid dynamics (CFD) and rigid body dynamics (RBD) have been successfully fully coupled on high performance computing (HPC) platforms for "Virtual Fly-Outs" of guided munitions identical to actual free flight tests in the aerodynamic experimental facilities. For the first time, this integrated capability now allows time-accurate truly coupled CFD/RBD computations to simultaneously predict the free flight aerodynamics and compute the actual flight trajectories of both spin and fin stabilized projectiles and missiles with and without flight control maneuvers using microjets or control surfaces such as canards. Computed positions and orientations of the projectiles have been compared with actual data measured from free flight tests and are found to be generally in good agreement. Unsteady numerical results obtained from the coupled method show the flow field, the aerodynamic forces and moments, and the flight trajectories of the projectiles. Computed results obtained for a complex configuration with canard-control pitch-up maneuver in a virtual fly-out show the potential of these techniques for providing the actual time-dependent response of the flight vehicle and the resulting unsteady aerodynamics.

1. INTRODUCTION

Understanding the aerodynamics of projectiles, rockets, and missiles is critical to the design of stable configurations and contributes significantly to the overall performance of weapon systems [1-3]. The prediction of aerodynamic coefficients for these weapon systems is essential in assessing the performance of new designs. Numerical simulations have the potential of greatly reducing design costs while providing a detailed understanding of the complex aerodynamics associated with each change. Recently, we have made progress in coupling computational fluid dynamics and flight dynamics to perform required multidisciplinary simulations for moving body problems. This involves real-time multidisciplinary-coupled computational fluid dynamics/rigid body aerodynamics computations for the entire flight trajectory of a complex guided projectile system. It can lead to accurate determination of aerodynamics, critical to the low-cost development of new advanced guided projectiles, rockets, missiles, and smart munitions.

Improved computer technology and state-of-the-art numerical procedures now enable solutions to complex, 3-D problems associated with projectile and missile aerodynamics. Modern guided munitions for future combat systems require the use of complex control surfaces (fins and canards), control mechanisms, and/or the use of flow technologies such as microjet gas generators to provide maneuver authority. The aerodynamic flow fields over these Army weapons are complex involving non-linear flow-physics especially during and after control maneuvers. For maneuvering munitions however, very limited data is available during and after control maneuvers [4-5], and there is a lack of knowledge and understanding of the associated unsteady aerodynamics. Accurate numerical modeling of this unsteady aerodynamics has been found to be challenging both in terms of time-accurate solution techniques and computing resources required. Our goal is to be able to perform time-accurate multidisciplinary-coupled computational fluid dynamics (CFD) and rigid body dynamics (RBD) computations for complex guided projectiles with control maneuvers using microjets and/or control surfaces such as fins/canards. As part of a DOD High Performance Computing Grand Challenge Project, the present work is focused on the coupling of CFD and rigid body dynamics (RBD) techniques for simultaneous prediction of the unsteady free-flight aerodynamics and the flight trajectory of projectiles. In other words, can we perform physics-based fly-outs of the projectiles on the supercomputers and accurately predict the unsteady aerodynamics and flight behavior of projectiles in actual flights?

As stated earlier, knowledge of the detailed aerodynamics of maneuvering guided smart weapons is rather limited especially during control maneuvers [4-5] at the present time. Multidisciplinary computations can provide detailed fluid dynamic understanding of the unsteady non-linear aerodynamics processes involving

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the maneuvering flight of modern guided weapon systems. Such knowledge cannot be easily obtained by any other means. CFD combined with HPC can now begin to accurately describe the relevant processes of great value. Up to now, the physics of this unsteady control maneuver phenomenon has not been well understood and advanced integrated high fidelity multidisciplinary numerical predictive capabilities did not exist for truly realistic flight simulation of these guided munitions. However, the research effort described here has led to an integrated multidisciplinary numerical capability to accurately predict and provide a crucial understanding of the complex flow physics associated the unsteady aerodynamics and flight dynamics of modern guided projectile and missile configurations. High performance coupled CFD/RBD techniques were developed and applied for the design and analysis of a supersonic Hit-to-Kill finned projectile and a spinning projectile with micro-adaptive flow control for trajectory correction. In addition, these advanced computational techniques have been extended and applied to a complex configuration with canard-control maneuver during its virtual flight. The advanced CFD capability used here solves the unsteady Navier-Stokes equations, incorporates unsteady boundary conditions and a special coupling procedure. The present research is a big step forward in that it allows "virtual fly-out" of projectiles on the supercomputers, and for the first time, it predicts the actual fight paths of a projectile and all the associated unsteady free-flight aerodynamics using coupled CFD/RBD techniques in an integrated manner.

2. NUMERICAL PROCEDURE

A real-time accurate approach is used in the present work; however, time-accurate computations require much greater computer resources. The real-time accurate approach also requires that the six-degrees-of-freedom body dynamics be computed at each repetition of the fluid flow solver. In three-dimensional space, a rigid object has six degrees of freedom: three translations and three rotations. The six-degree-of-freedom code computes linear and angular velocities as well as the orientation of the missile, which are used as input to the computational fluid dynamics code. In turn, the aerodynamic forces and moments obtained from the flow solver are used to solve the 6-dof body dynamics before moving on to the next time step. This procedure allows one to perform real-time multidisciplinary-coupled computational fluid dynamics/rigid body aerodynamics computations for the partial or entire flight trajectory of a complex guided projectile system.

The CFD capability used here solves the Navier-Stokes equations [6-9] and incorporates advanced boundary conditions and grid motion capabilities. The present numerical study is a big step forward and a direct extension of that research which now includes numerical simulation of the actual fight paths of the projectile using coupled CFD/RBD techniques using real-time accurate approach. The complete set of 3-D time-dependent Navier-Stokes equations is solved in a time-accurate manner for simulations of actual flights. The basic numerical framework in the code contains unified-grid, unified-physics, and unified-computing features. The user is referred to these references for details of the basic numerical framework. The 3-D time-dependent Reynolds-averaged Navier-Stokes (RANS) equations are solved using the finite volume method [7]:

$$\frac{\partial}{\partial t}\int_V \mathbf{W} dV + \oint [\mathbf{F} - \mathbf{G}] \cdot dA = \int_V \mathbf{H} dV \qquad (1)$$

where **W** is the vector of conservative variables, **F** and **G** are the inviscid and viscous flux vectors, respectively, **H** is the vector of source terms, V is the cell volume, and A is the surface area of the cell face.

Second-order discretization was used for the flow variables and the turbulent viscosity equation. The turbulence closure is based on topology-parameter-free formulations. Two-equation [6] and higher order hybrid RANS/LES [10,11] turbulence models were used for the computation of turbulent flows. The hybrid RANS/LES approach is well suited to the simulation of unsteady flows and contains no additional empirical constants beyond those appearing in the original RANS and LES sub-grid models. With this method a regular RANS-type grid is used except in isolated flow regions where denser, LES-type mesh is used to resolve critical unsteady flow features. The hybrid model transitions smoothly between an LES calculation and a cubic k-ε model, depending on grid fineness. For computations of unsteady flow fields that are of interest here, dual time-stepping as described below was used to achieve the desired time-accuracy [12].

An unique feature of the present coupled approach is the full grid motion capability that allows the grid to move translate and rotate as the projectile flies down the rage, since the grid velocity is assigned to each mesh point. To account for rigid body dynamics, the grid point velocities are set as if the grid is attached to the rigid body with six degrees of freedom (6 DOF). As shown schematically in Figure 1, the six degrees of freedom comprise of the three spatial coordinates (x,y,z) and the three Euler angles, roll, pitch, and yaw (ϕ, Φ, Ψ). For the rigid body dynamics, the coupling refers to the interaction between the aerodynamic forces/moments and the dynamic response of the projectile/body to these forces and moments. The forces and moments are

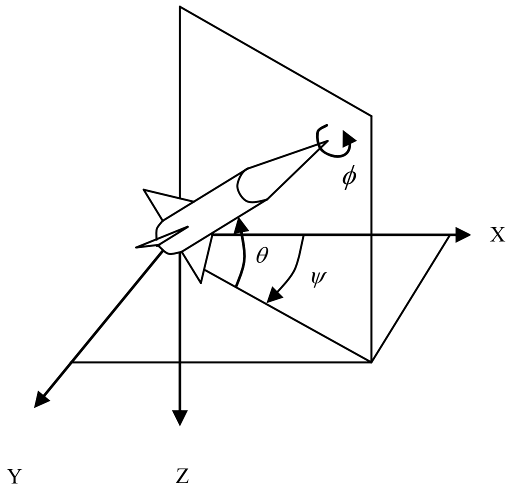


Figure 1. Rigid Body Dynamics Schematic.

computed every CFD time step and transferred to a 6DOF module which computes the body's response to the forces and moments. The response is converted into translational and rotational accelerations that are integrated to obtain translational and rotational velocities and integrated once more to obtain linear position and angular orientation. From the dynamic response, the grid point locations and grid point velocities are set. Both CFD and RBD computations are performed at every time step in a fully coupled manner.

3. RESULTS

Numerical simulations of the virtual fly-outs have been carried out at ARL Major Shared Resource Center using 64 processors on a Linux Cluster and requiring hundreds of thousands of hours as part of Grand Challenge Project for three different projectiles at different flight conditions.

3.1 Finned Projectile in Supersonic Flight

Computed results have been obtained at an initial supersonic speed, M = 3.0 and angle of attack, α = -5° for a finned projectile with a base cavity using an unstructured time-accurate Navier-Stokes computational technique that includes grid motion capabilities. Dual time-stepping was used to achieve the desired time-accuracy for time-accurate CFD computations of unsteady flow fields. In addition, the projectile in the coupled CFD/RBD simulation actually moved along with its grid as it flew downrange.

The supersonic projectile modeled in this study is an ogive-cylinder-finned configuration (see Figure 2). The length of the projectile is 121 mm and the diameter is 13mm. The ogive nose is 98.6 mm long and the

Figure 2. Supersonic finned projectile.

afterbody has a 22.3 mm, 2.5° boat-tail. Four fins are located on the back end of the projectile. Each fin is 22.3 mm long and 10.16 mm thick. An unstructured computational mesh was generated for this projectile. In general, most of the grid points are clustered in the boundary-layer and afterbody fin regions. The total number of grid points is about 4 million for the full grid.

Here, our primary interest is in the development and application of coupled CFD and RBD techniques for accurate simulation of the free flight aerodynamics and flight dynamics of the projectile in supersonic flight. The first step was to obtain the steady state results for this projectile at a given initial supersonic velocity. Also imposed were the angular orientations at this stage. Corresponding converged steady state solution was then used as the starting condition along with the other initial conditions for the computation of coupled CFD/RBD runs. Numerical computations have been made for these cases at an initial velocity of 1034 m/s. The simulations were started a small distance away from the muzzle. The corresponding initial angle of attack was, $\alpha = 4.9^{o}$ and initial spin rate was 2500 rad/s. Figures 3 and 4 show the computed z- and y-distances as a function of x (or, the

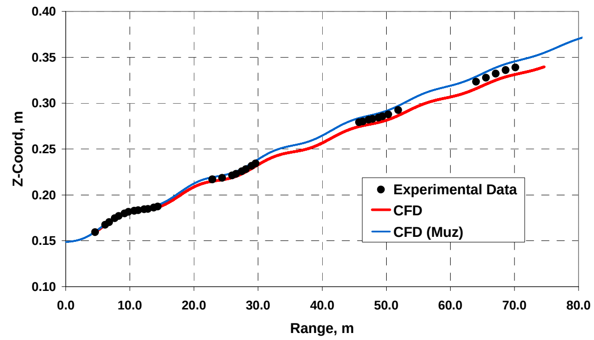


Figure 3. Computed z distance vs. range.

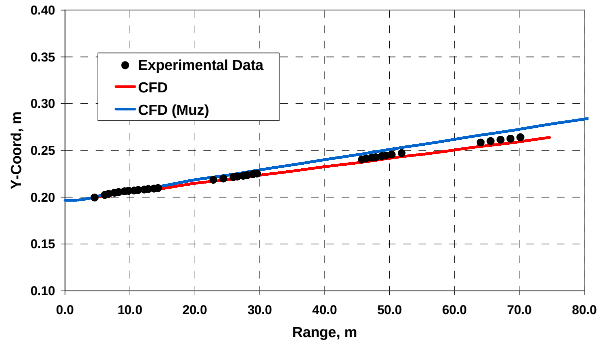


Figure 4. Computed y distance vs. range.

range). The computed results are shown in solid lines and are compared with the data measured from actual flight tests. Figure 5 shows the computed pressure contours at a given time or at a given location in the trajectory. It clearly shows the orientation of the body at that instant in time and the resulting asymmetric flow field due to the body at angle of attack. The orientation of the projectile of course changes from one instant in time to another as the projectile flies down range. Figure 6 shows the variation of the Euler pitch angle with distance traveled. As seen in this figure, both the amplitude and frequency in the Euler angle variation are predicted very well by the computed results and match extremely well with the data from the flight tests. One can also clearly see that the amplitude damps out as the projectile flies down range i.e. with the increasing x-distance. As shown in figure 7, similar behavior is observed with the Euler yaw angle and it damps out with the increasing x-distance. Computed results again compare very well with the measured data from the flight tests.

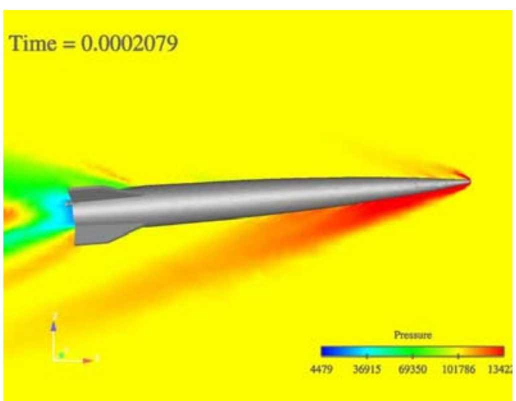


Figure 5. Computed pressure contours.

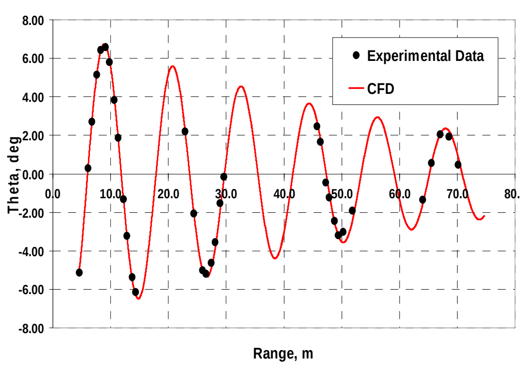


Figure 6. Euler pitch angle vs. x-distance.

The time histories of the pitch and yaw angles are often customarily presented as a motion plot where the pitch angle is plotted versus the yaw angle during the flight of the projectile. It represents the path traversed by the nose of the projectile during the flight trajectory

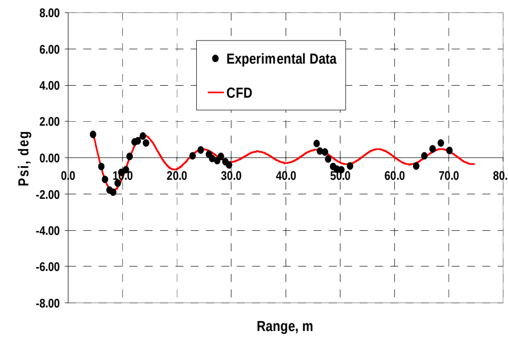
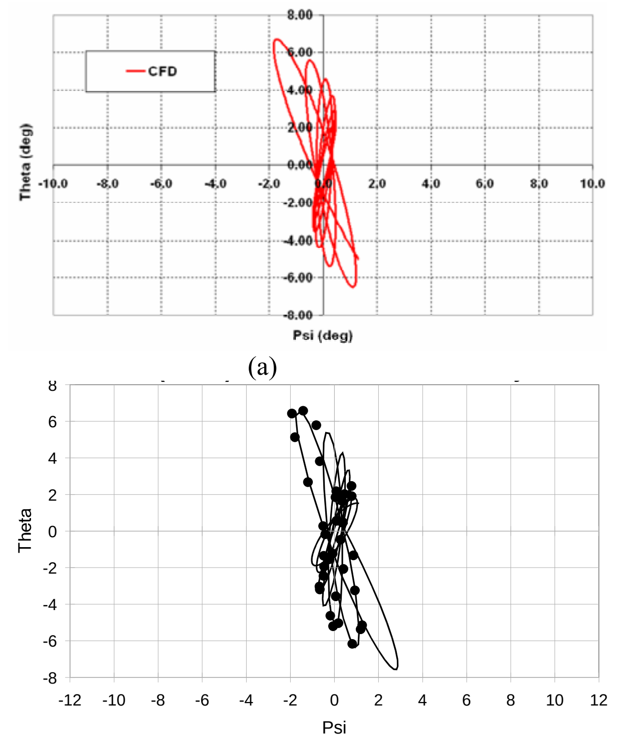


Figure 7. Euler yaw angle vs. x-distance.



(a)

(b)

Figure 8. Motion plot (a) computation, (b) flight test

(looking forward from the back of the projectile). Such motion plots are shown in Figure 8. This figure shows the comparison of the motion plots obtained both from the numerical simulations and the 6DOF analysis of the flight results from ARFDAS, software commonly used for this purpose. Computed results match very well with the experimental flight test results. The unsteady simulations took thousands of hours of CPU time on a Xeon PC cluster system running with either 32 to 64 processors.

3.2 Spinning Projectile in Subsonic Flight both with and without Flow Control

The capability of the multidisciplinary coupled CFD and RBD techniques was further demonstrated by

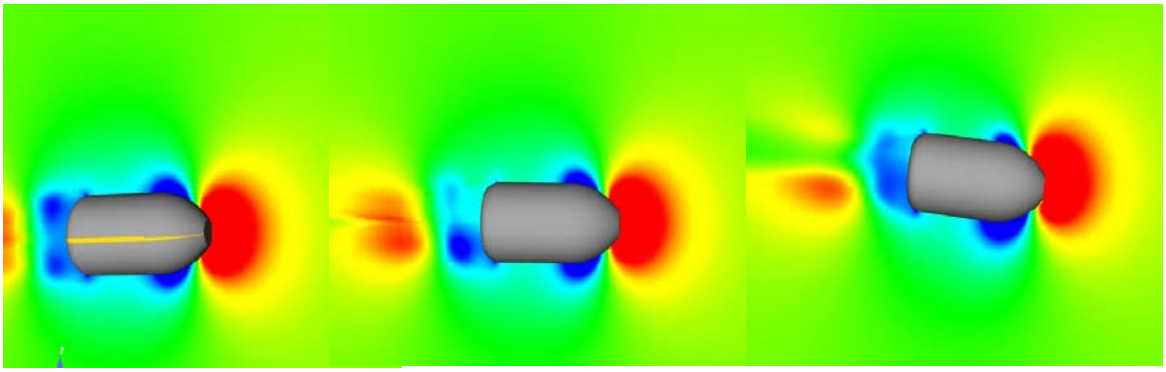


Figure 9. Instantaneous pressure contours at three different instances during the flight.

modeling the actual flight of a spinning projectile (Figure 9) with and without micro- adaptive flow control. These simulations enabled the development of the flight control technology required to divert the spinning projectile, and the design of the flight test and validation hardware. The results of the simulations were used in an open-loop flight test that clearly indicated that MAFC can be used to divert a spinning projectile in flight. The unsteady nature of the time histories of computed side force (F_Y) resulting from the unsteady jet interaction flow field is clearly evident (Figure 10). The effect of the jet is stronger as evidenced by the larger mean amplitudes seen in the forces. Figure 11 shows the variation of y-distance as function of the range both with and without the micro-jet. These computed results strongly indicate that applying the jet in the positive y-direction moves the projectile in the same positive direction with little or no effect on the other aerodynamic forces. These results show the potential to gain fundamental understanding of the complex, flow phenomena and time-dependent aerodynamic wake interactions associated with micro-jet control for spin-stabilized munitions.

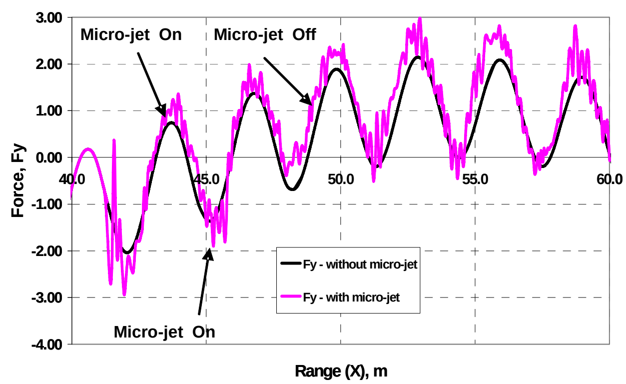


Figure 10. Comparison of computed side force, with and without micro-jet.

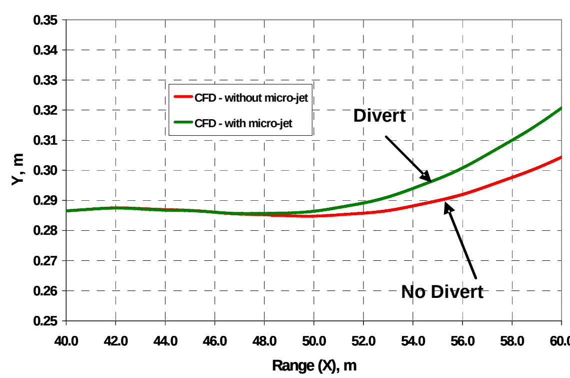


Figure 11. Comparison of the computed Y distance, with and without micro-jet.

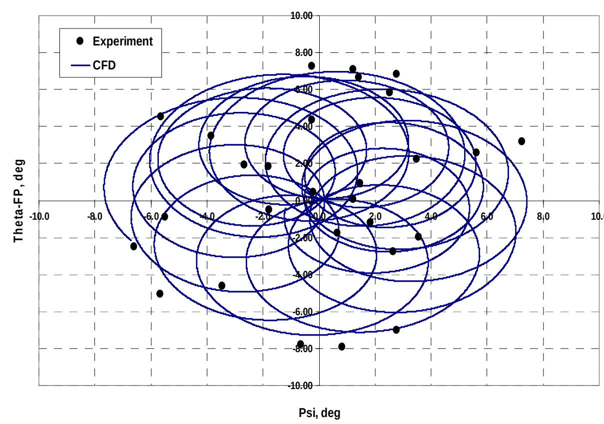


Figure 12. Motion plot for the spinning projectile .

The time histories of the pitch and yaw angles are shown in Figure 12 as a motion plot. Again, it represents the path traversed by the nose of the projectile during the flight trajectory (looking forward from the back of the projectile). Computed results match well with the flight data shown in solid symbols.

3.3 Complex Projectile in Supersonic Flight with Canard maneuver

Another case considered in the study is a complex canard-controlled finned projectile. Here, the control maneuver is achieved by the two horizontal canards in the nose section (Figs. 13-15). Unstructured Chimera overlapping grids were used (see Fig. 13) and solutions have been obtained for several canard deflection cases. Figure 14 shows the computed pressure contours at M =

3.0 and $\alpha = 0°$ for a canard deflection of 20 deg. Although not shown here, this produces lift that can be used to obtain increased range. A typical result is shown in Figure 15 for the canard deflection of 20° (high pressure region shown in red and low pressure region in blue).

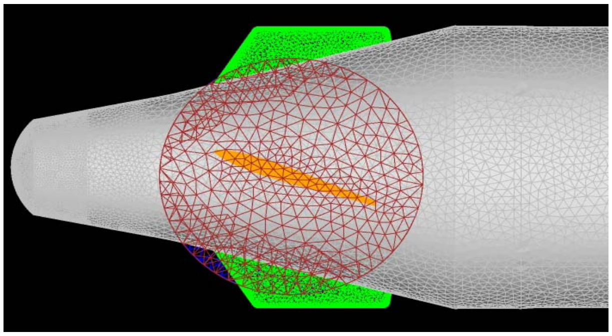


Figure 13. Unstructured Chimera mesh in the nose region (side view).

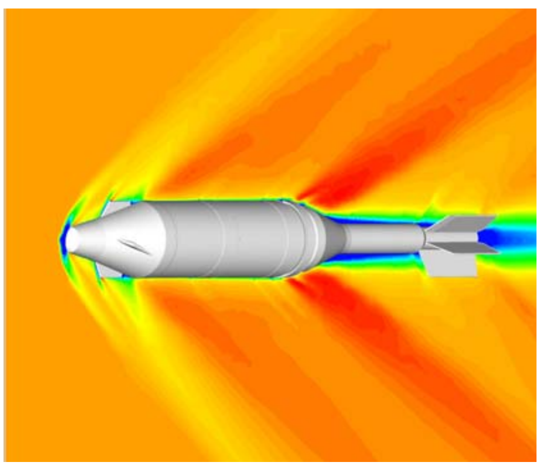


Figure 14. Computed pressure contours, M = 3.0, α = 0°.

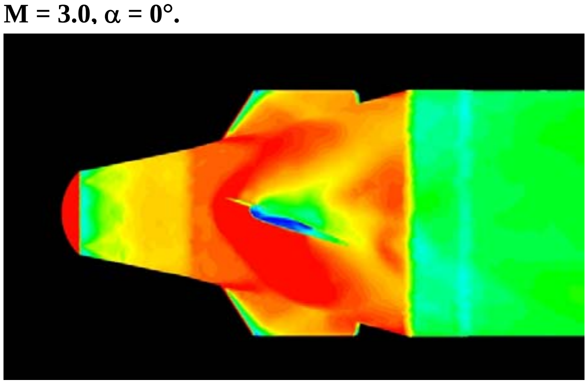


Figure 15. Computed surface pressure contours in the nose section, M = 3.0, α = 0°.

Some results for a "pitch maneuver" are shown in Figures 16 and 17. In this case, the two horizontal canards are rotated down 10° in 0.01 sec, held there for the next 0.01 sec, and then deflected back to their horizontal positions in the next 0.01 sec. This maneuver generates a lot of lift force (see Figure 16) until the end of this virtual fly-out simulation (time = 0.145 sec). This results in the nose of the projectile pitching up and the z-distance of the center of gravity of the projectile increasing from 0 to 0.5 meter (see Figure 17). Also, shown in this figure is the Euler pitch angle which goes from 0 to a peak value of about -16° (nose-up corresponds to negative Euler pitch angle). These results clearly show a large effect on the time-dependent response of the projectile subject to a canard maneuver.

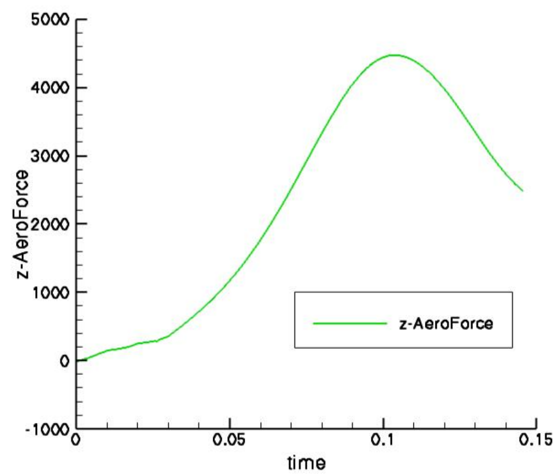


Figure 16. Time history of lift force.

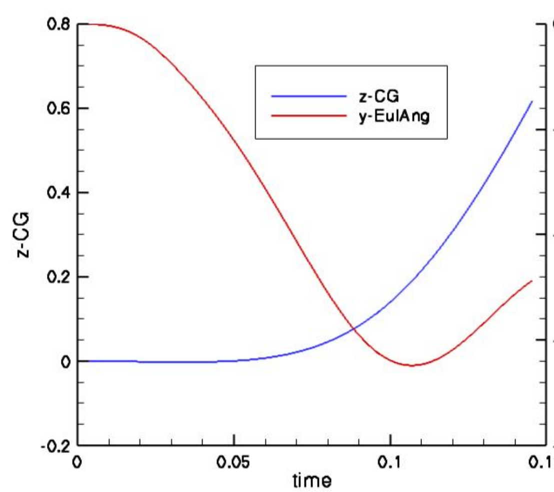


Figure 17. Time history of z-distance (center of gravity) and Euler pitch angle.

CONCLUSIONS

This paper describes a new coupled CFD/RBD computational study undertaken to determine the free flight aerodynamics and flight dynamics of projectiles both with and without control maneuvers in an integrated manner. Advances made in CFD and high performance computing have been exploited to compute time-accurate aerodynamics associated with the free flight of a finned projectile at supersonic velocities and a spinning projectile at subsonic speed. Computed positions and orientations of the projectiles have been compared with actual data measured from free flight tests and are found to be generally in good agreement. These advanced computational techniques have been extended and applied to a complex configuration with canard-control maneuver. Computed results show the potential of these techniques for providing the actual time-dependent response of the flight vehicle induced by a canard-maneuver in a virtual fly-out.

This research is at the forefront of technology in projectile aerodynamics area and represents a major increase in capability for simultaneously determining the high-fidelity unsteady aerodynamics and flight dynamics of munitions in a new way via virtual fly-outs through supercomputers. This coupled approach forms the basis for future multidisciplinary, time-dependent computations of advanced maneuvering munitions and provides an affordable route to lethal precision-guided weapons and improved accuracy of current and future small to medium caliber projectiles with a high degree of maneuverability.

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Aerodynamics Branch

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TECHNOLOGY TO WIN

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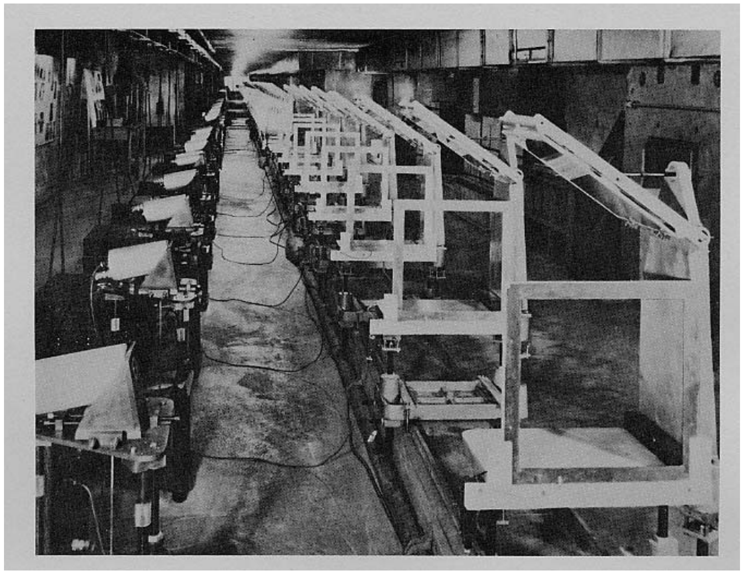
AMERICA'S ARSENAL FOR THE BRAVE

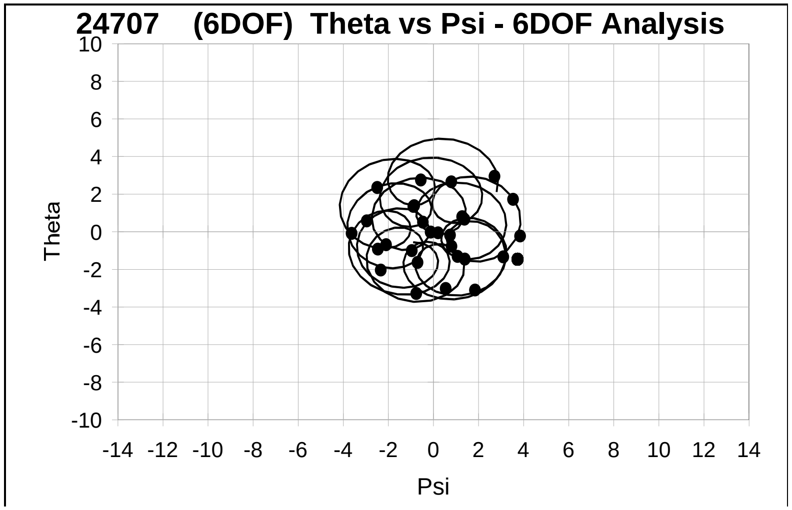
Projectile Aerodynamics

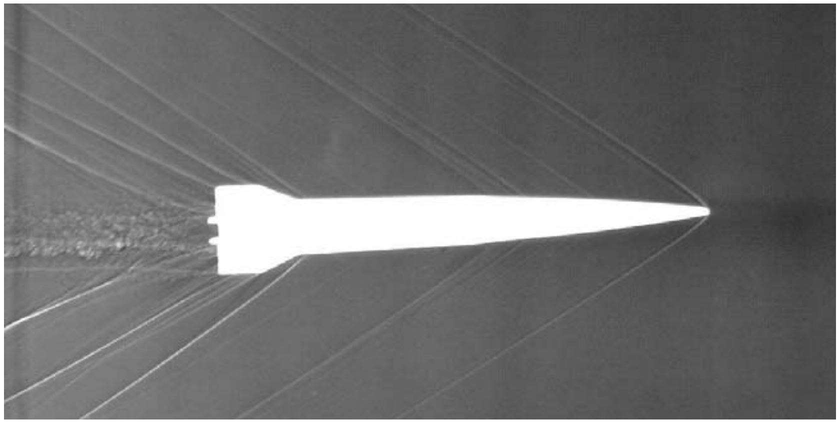
- Actual flight testing
  - Experimental facilities (Aero Range, Transonic Range)
  - Measure the positions and orientations; get Aero from 6-DOF fits
- Computational Fluid Dynamics (CFD)
  - Steady-State Aerodynamics
  - Unsteady Aerodynamics for Magnus, Pitch Damping, Control Maneuvers etc.
- Multidisciplinary CFD and 6-DOF Rigid Body Dynamics (RBD) Coupling for “Virtual Fly-Outs” --- A New Approach
  - Simulate actual free flight
  - Integrated unsteady aerodynamics/flight dynamics
  - Control maneuvers (canard-controlled)
  - Dynamic response of the projectile due to control maneuver

Aerodynamics Experimental Facility



- Gun launch
- Spark Range Reduction
  - Computer system triggers spark source, takes images of passing projectile
  - Horizontal and vertical film utilized at each station
    - Accurately determine projectile orientation
      - Pitch, Roll, Yaw
      - X, Y, Z
    - Post-processing of data read from spark shadowgraphs (flow fields)
    - Completes 6DOF fit of range data
  - Aerodynamic coefficients determined
  - Characterize observed flight dynamics

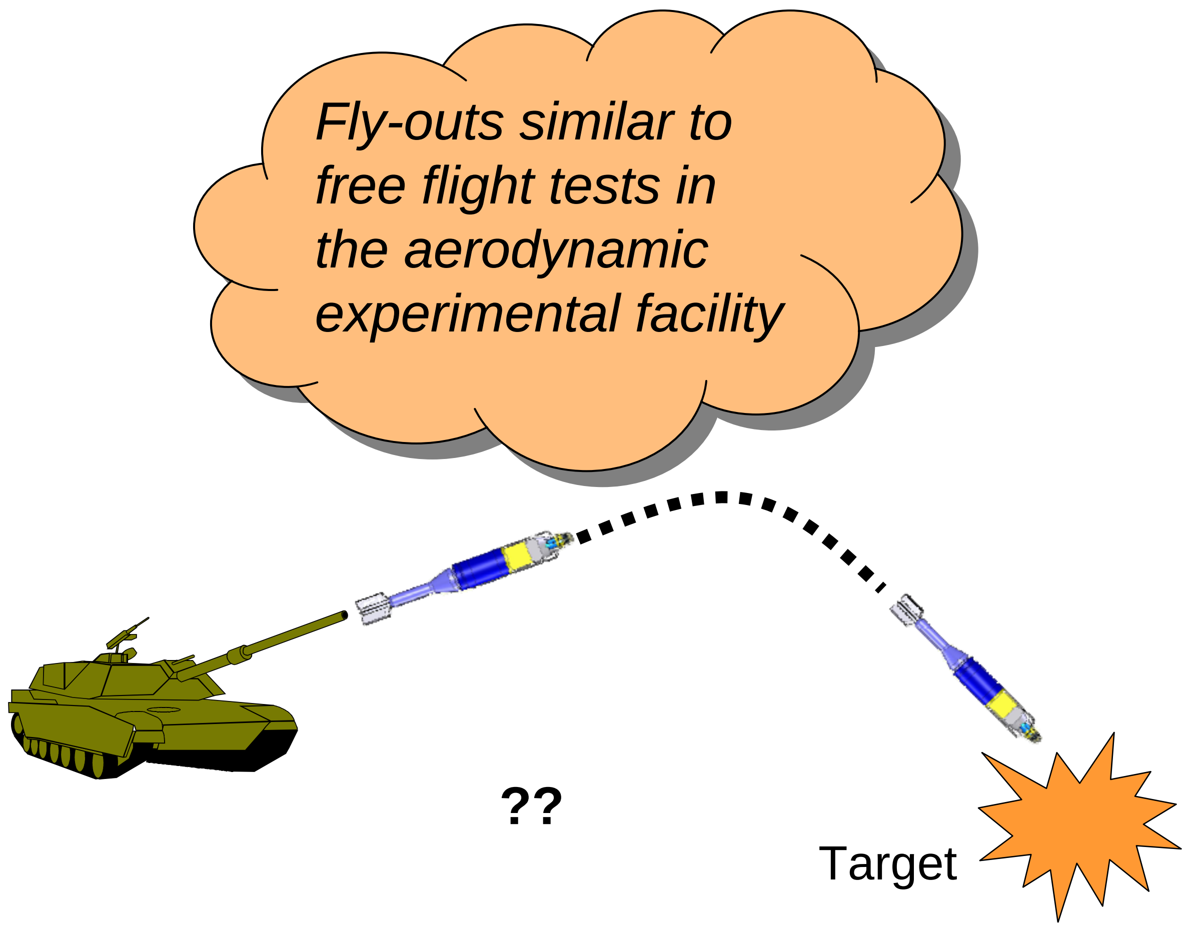




GOAL: Virtual Fly-Outs of Projectiles

DOD Grand Challenge Project

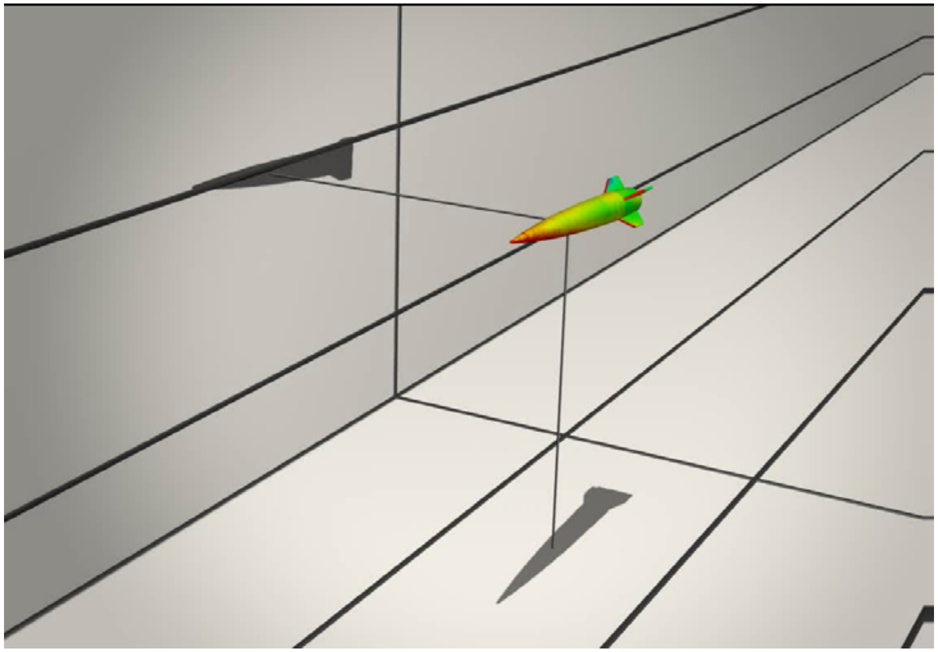
Coupled CFD/RBD simulations to compute the trajectory of in-flight spinning and finned projectiles on HPC platforms

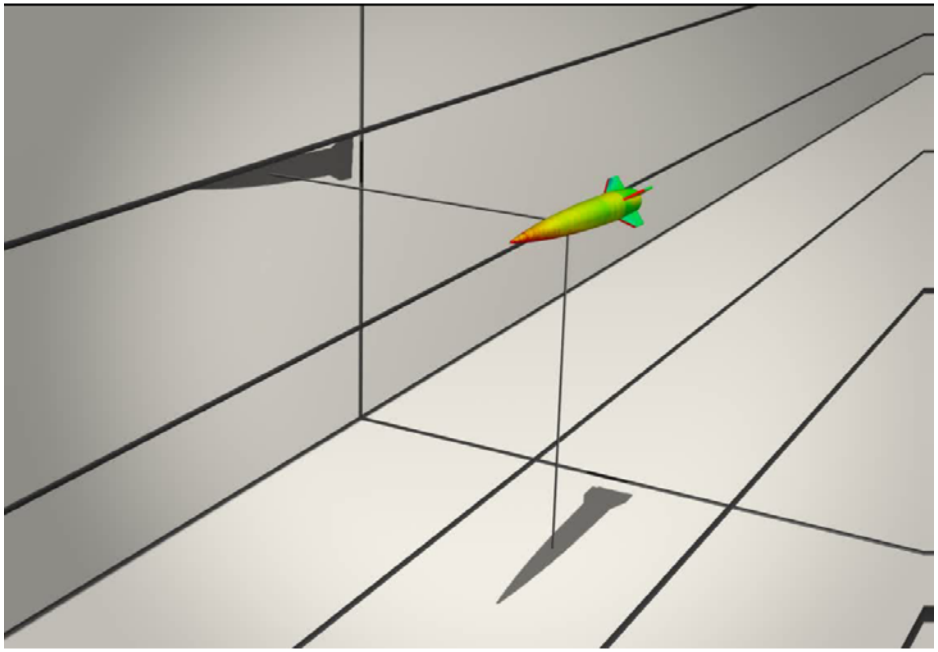


- **Integrated unsteady aerodynamics/flight dynamics**
- **Unsteady maneuvers**
  - **Jet controlled**
  - **Canard control**
- **Finned projectile (Supersonic Flight)**
  - **Easier to compute**
  - **Data for Validation of computed results**
- **Spinning projectile with micro-adaptive flow control at subsonic a speed**
  - **Partial trajectory simulation**
  - **More difficult**

Examples of Good and Bad Flights

Integrated unsteady aerodynamics/flight dynamics



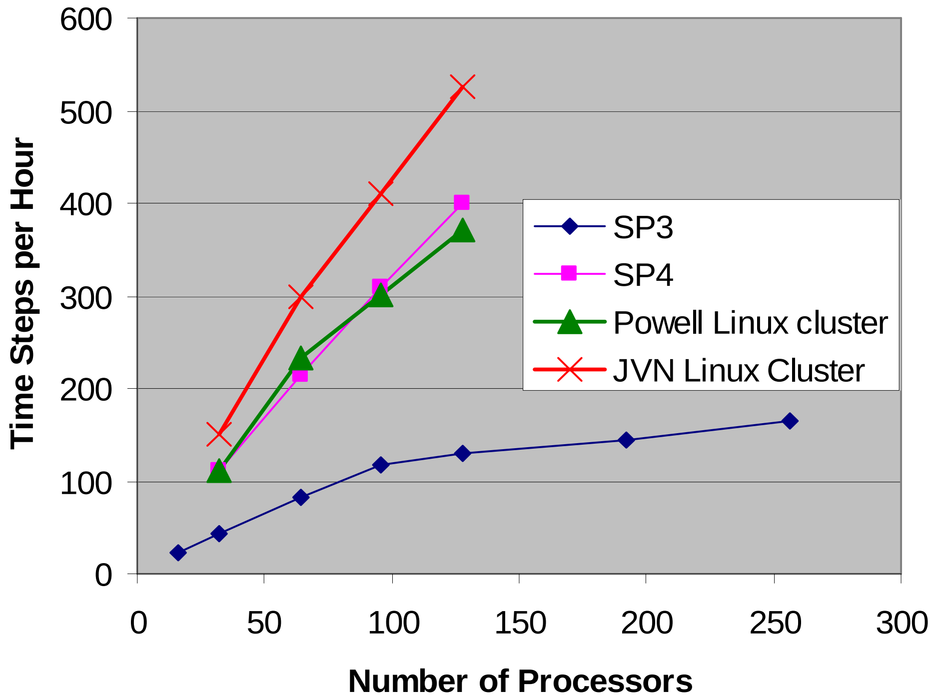


HIGH PERFORMANCE COMPUTING FLY-OUTS

ARL MSRC Systems used for Unsteady Flow Simulations

- IBM SP P3 (375 MHz, 64 node, 1024 Processors)
- IBM SP P4 (1.7 GHz, 4 node, 128 Processors)
- **Powell Linux cluster (3.06 GHz, 128 node, 256 Processors)**
- **JVN Linux Cluster (3.6 GHz, 1024 node, 2048 Processors)**

- **12 Million Point Hexahedral Grid**
- **7 Equations, k-e Turbulence model**



Virtual Fly-Outs of various projectiles were carried out typically with 32 to 64 processors on supercomputers at ARL MSRC requiring hundreds of thousands of CPU hours as part of the DoD HPC grand Challenge Project.

Multidisciplinary Computational Technique

CFD Computational Technique

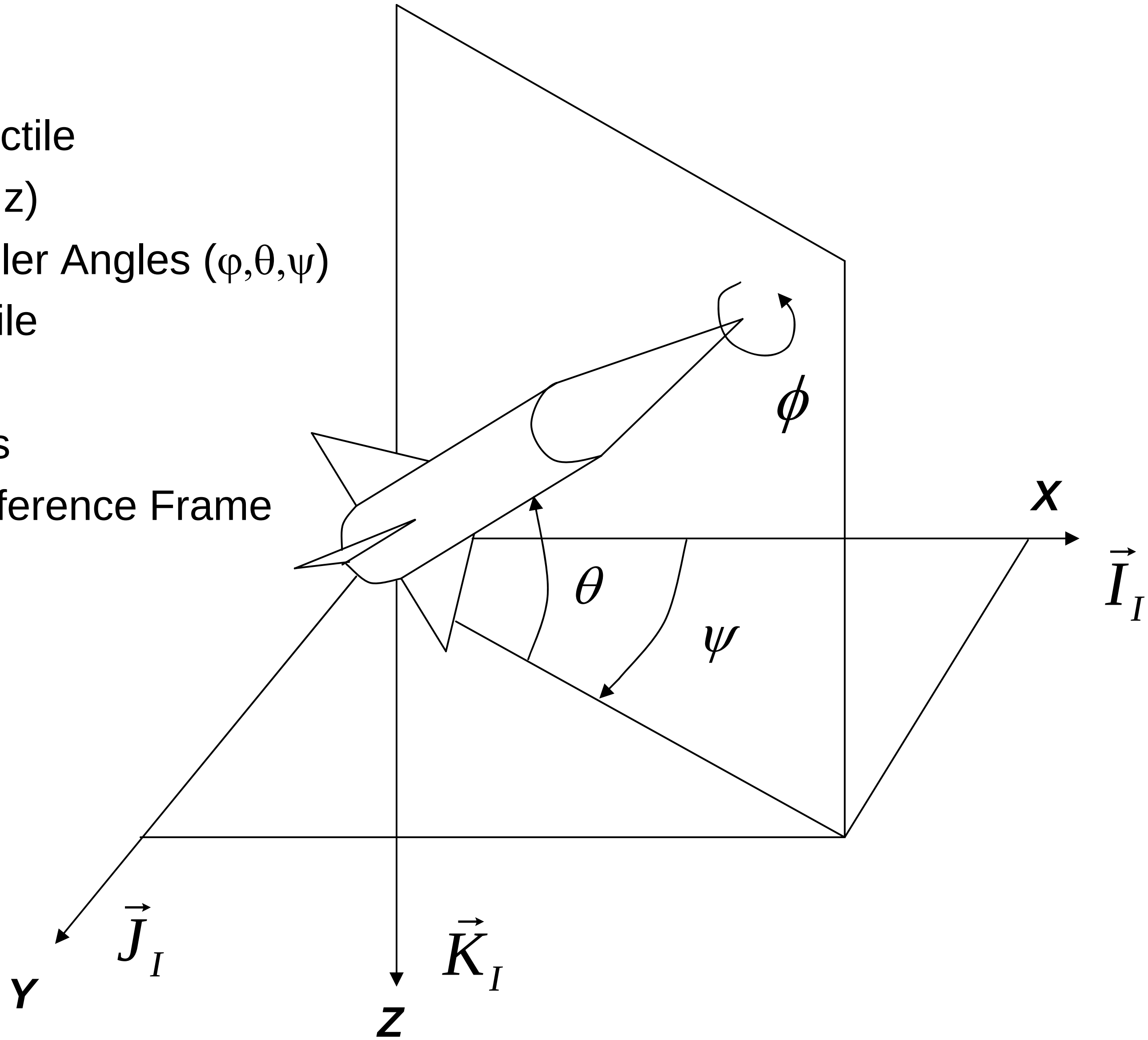
- 3-D Unsteady Navier-Stokes equations
- Dual Time-Stepping for transient flow computations
  - Two time-steps
  - First (outer) global or physical step –usually set to 1/100th of the period of oscillation
  - Second (inner) step – 5 to 10 inner iterations
- Grid Motion and BC:
  - Grid moves and rotates as the projectile moves and rotates
  - Free stream is preserved for arbitrary mesh and arbitrary mesh velocity

CFD/RBD COUPLING PROCEDURE

- 6-DOF equations solved at every CFD time-step
- CFD provides aerodynamic forces and moments
- 6-DOF provides the response of the body to the forces and moments
- The response is converted to translational and rotational accelerations
- Integrate the accelerations to obtain translational and rotational velocities
- Integrate once more to obtain linear position and angular orientations
- 6-DOF uses quaternions to define angular orientations
- From the dynamic response, grid point locations and velocities are set

6-DOF Rigid Body Dynamics

- Rigid Body 6 DOF Projectile
  - — Inertial Position (x,y,z)
  - — Body Orientation Euler Angles (φ,θ,ψ)
- Loads Acting on Projectile
  - — Weight
  - — Aerodynamic Forces
- Ground is an Inertial Reference Frame



Multidisciplinary CFD/RBD Fly-Outs

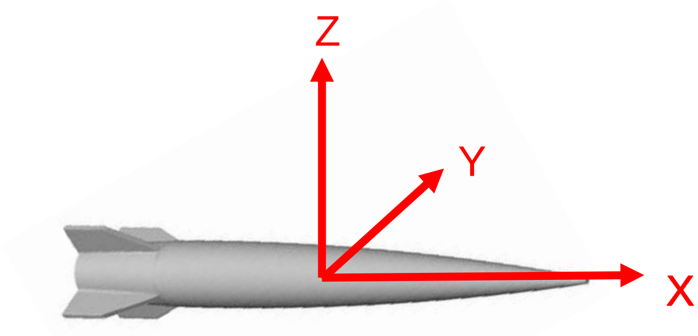
RESULTS

Finned Projectile in Supersonic Flight

Physical Properties and Initial Conditions

•Mass Properties

Projectile diameter = 0.013194 (m)
Mass = 0.484E-01 (kg)
Axial Inertia = 0.740E-06 (kg- m2)
transverse Inertia = 0.484E-04 kg- m2)
Length = 0.125908 (m)
C.G. (from the nose) = 0.057353 (m)



Initial Conditions at the First Station

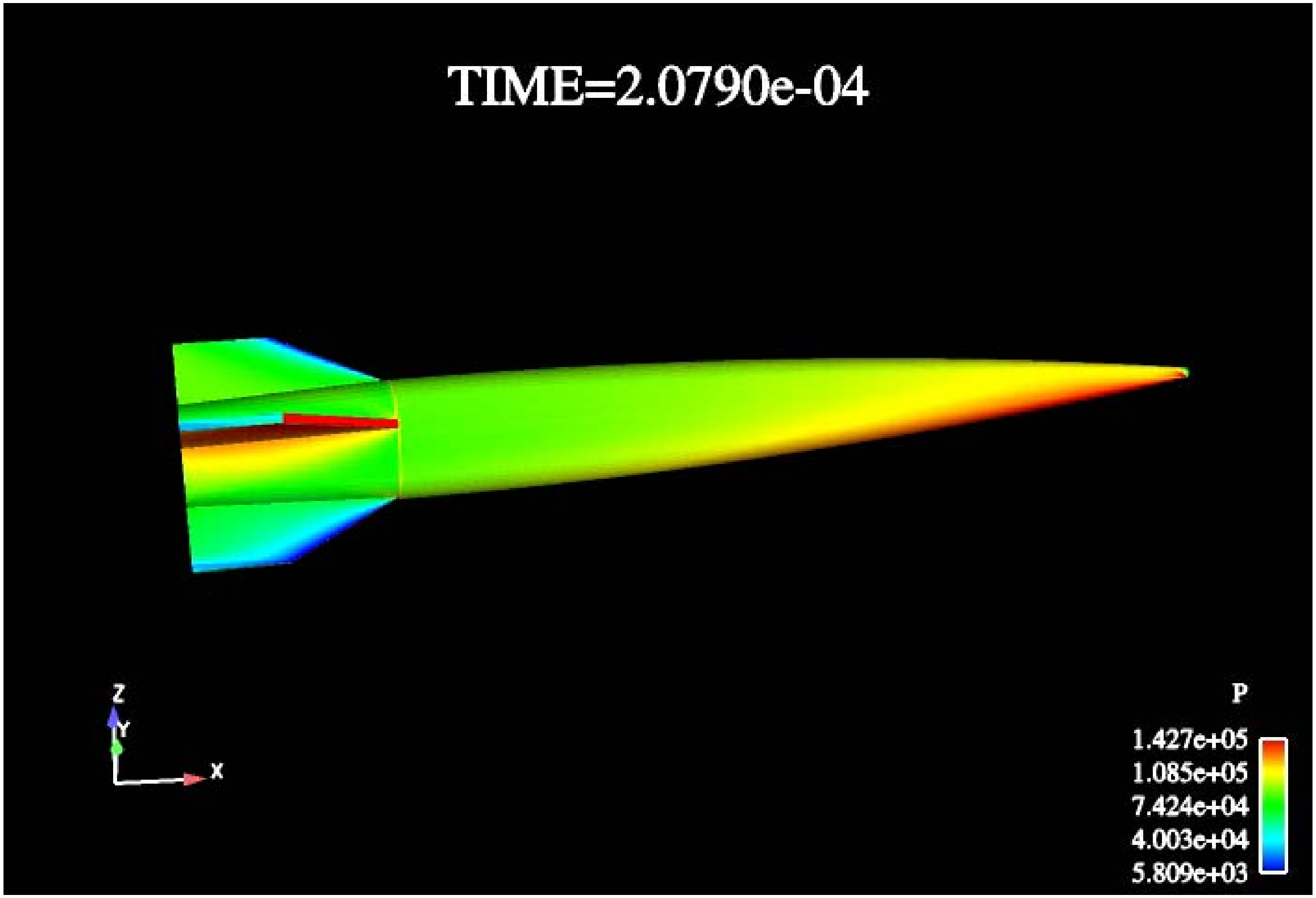
Pitch [THETA] (rad):	-0.088
Pitch Rate [Q](rad/sec):	52.802
Yaw [PSI] (rad):	0.023
Yaw Rate [R](rad/sec):	-22.233
Travel [X] (m):	4.593
Velocity-Missile [U] (m/sec):	1030.81
Horizontal Motion [Y] (m):	0.2
Hor. Rate-Missile [V] (m/sec):	-22.064
Vertical Motion [Z] (m):	0.159
Vertical Rate-Msle [W] (m/sec):	-86.278
Roll [PHI] (rad):	2.051
Roll Rate [P](rad/sec):	2518.39

Coordinate Definitions:

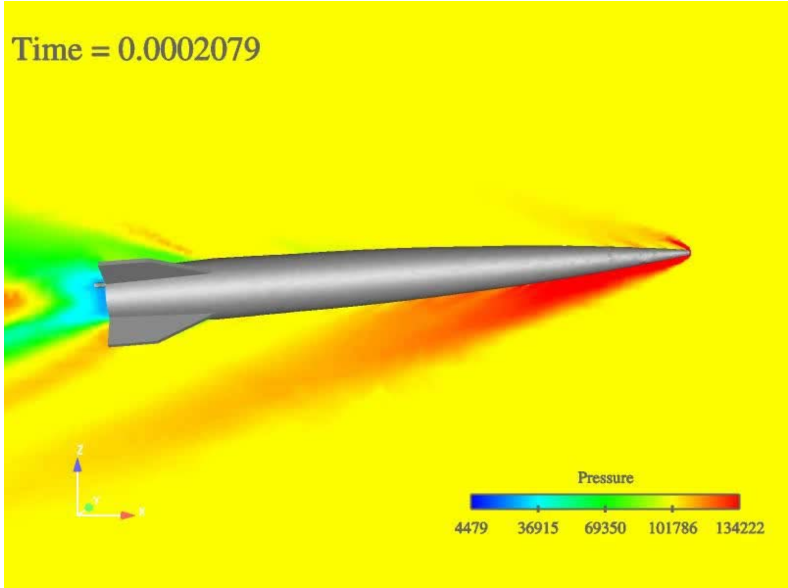
X - Downrange
Y - Cross Range (Positive to the left when viewed from the gun)
Z - Altitude (Positive up)
Φ - Euler Roll Angle (Positive clockwise when viewed from the rear of the projectile)
θ - Euler Pitch Angle (Positive nose down)
ψ - Euler Yaw Angle (Positive nose left when viewed from the rear of the projectile)
U - X Body component of velocity
V - Y Body component of velocity
W - Z Body component of velocity
P - Roll Rate (Positive clockwise when viewed from the rear of the projectile)
Q - Pitch Rate (Positive nose pitching down)
R - Yaw Rate (Positive nose yawing left when viewed from the rear of the projectile)

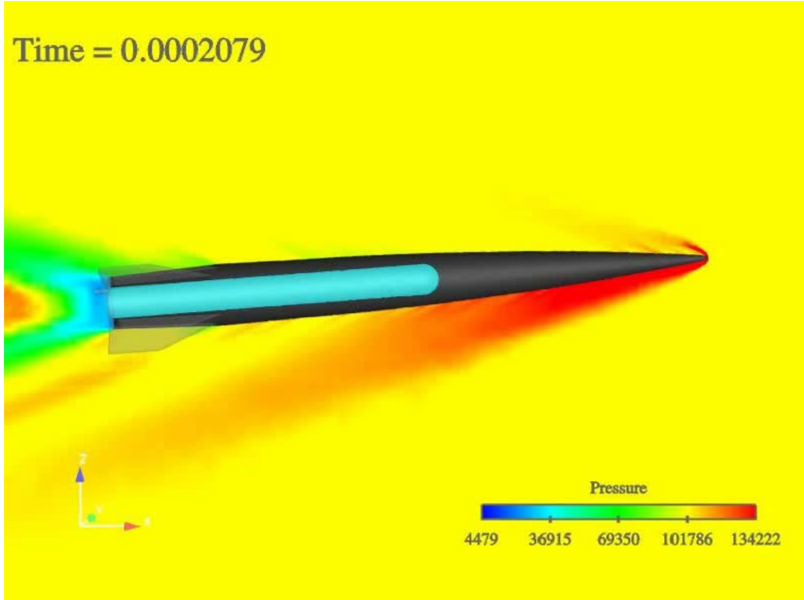
Computed Surface Pressures

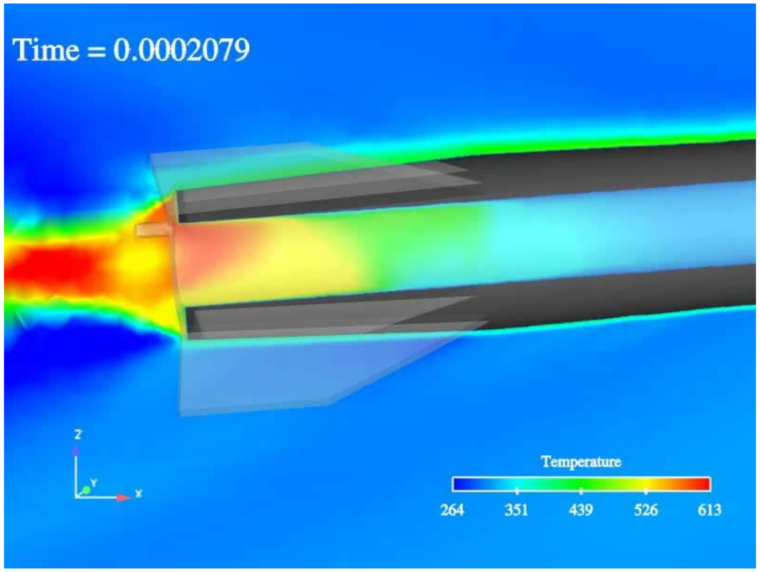
Initial Mach = 3.0

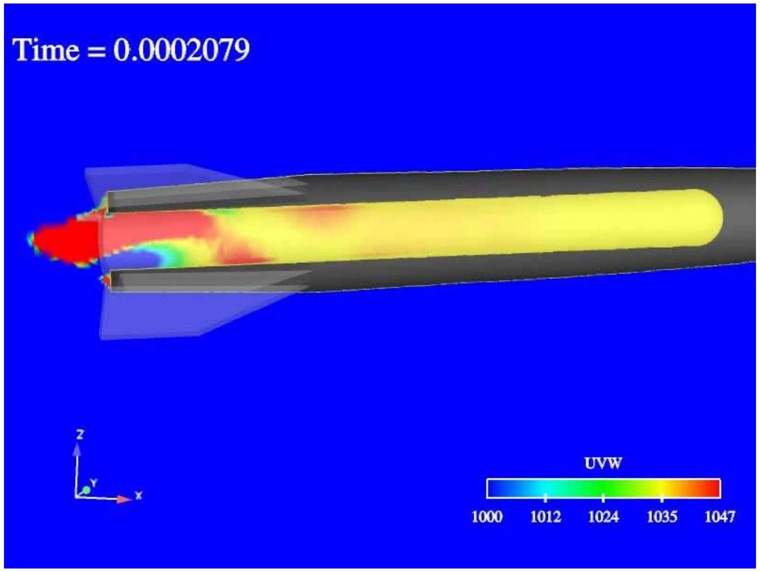


Computed Pressures
Initial Mach = 3.0



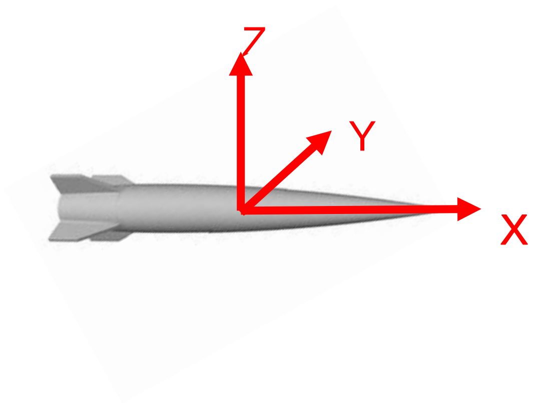




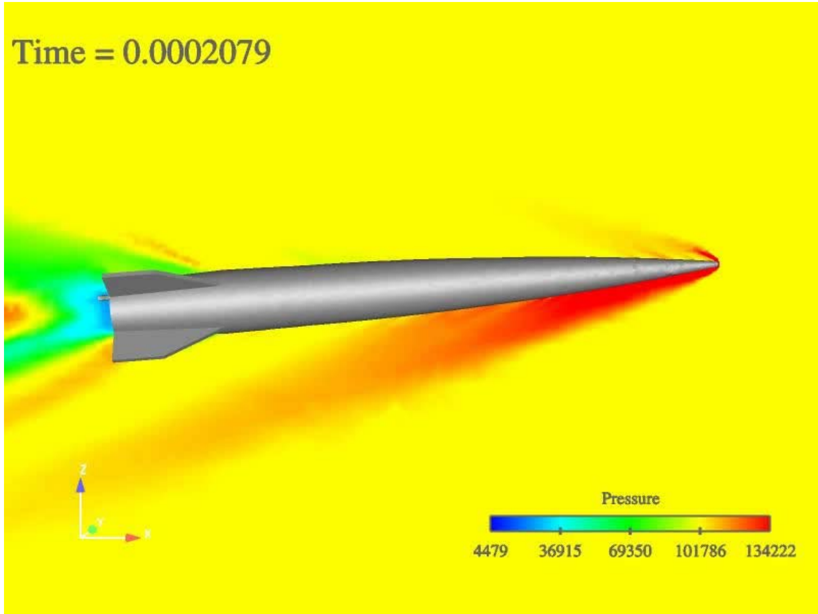


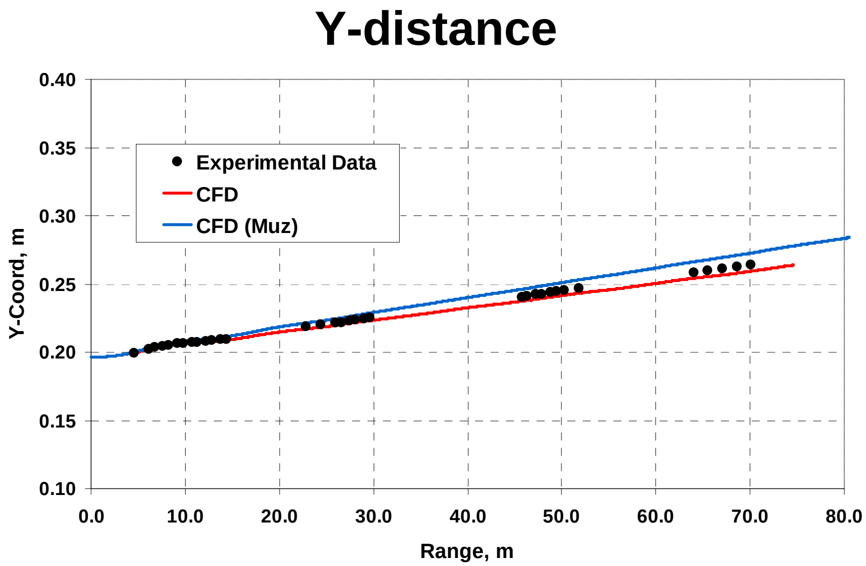
6-DOF Fly-out of a Finned Projectile

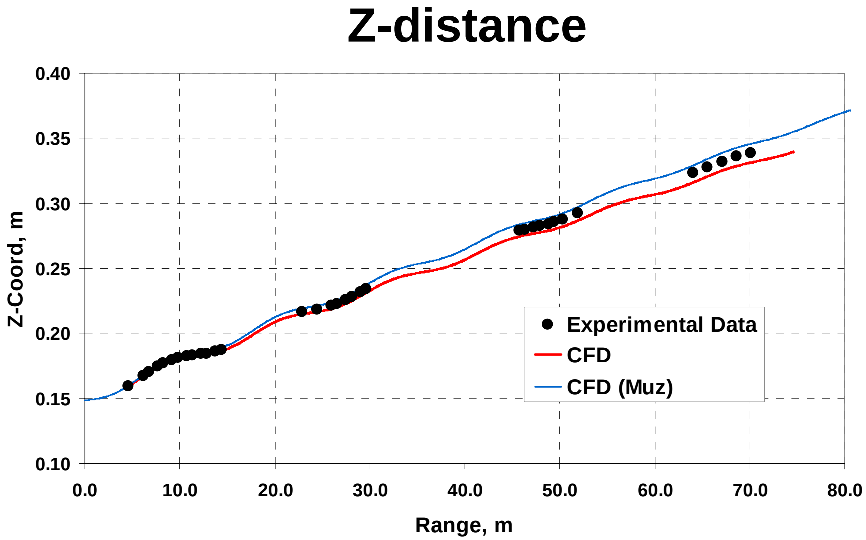
Initial Velocity, Mach = 3



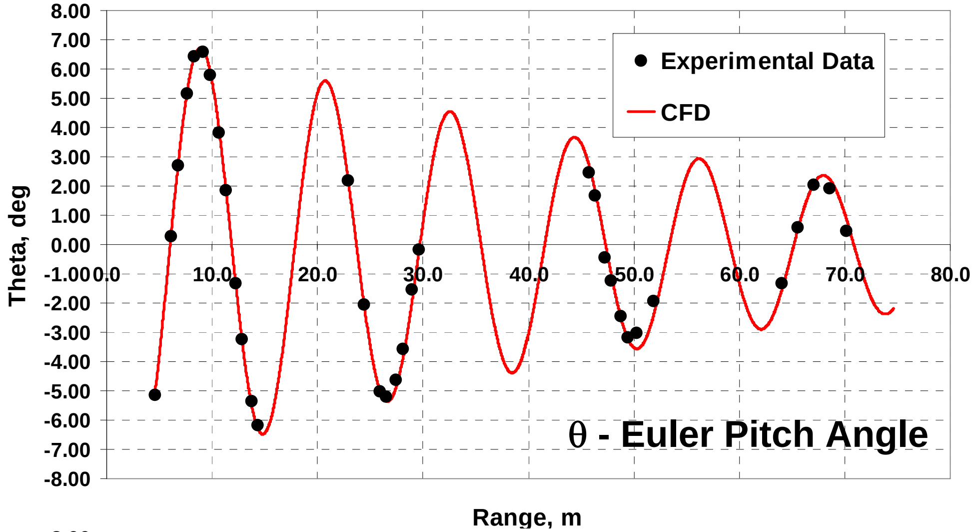
Computed pressures

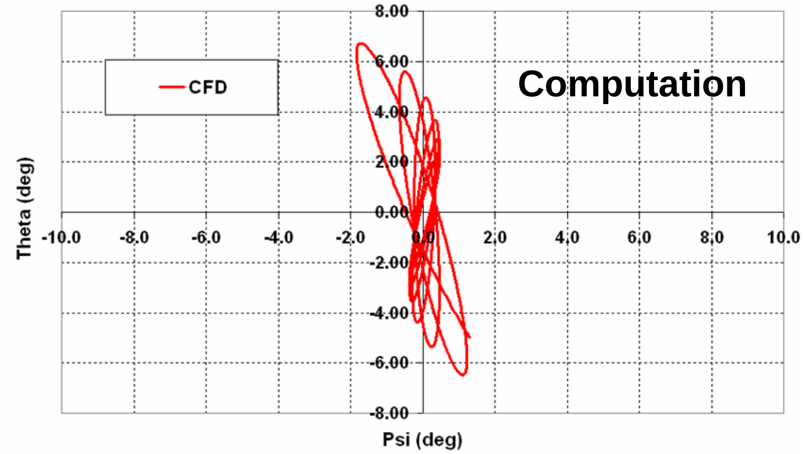




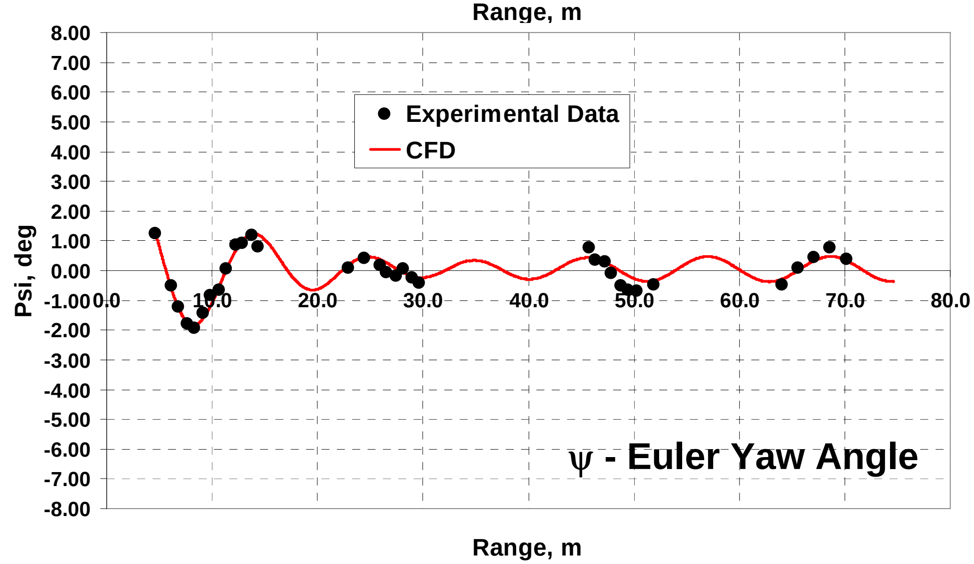


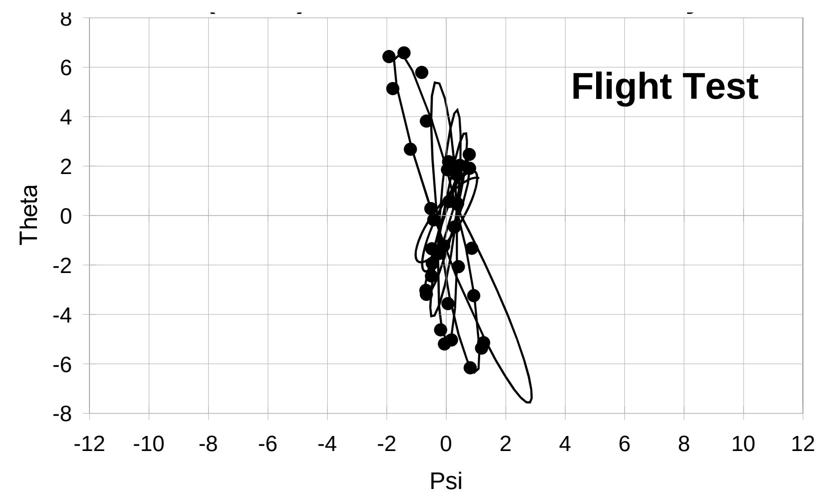
Comparisons of Computed Euler Angles





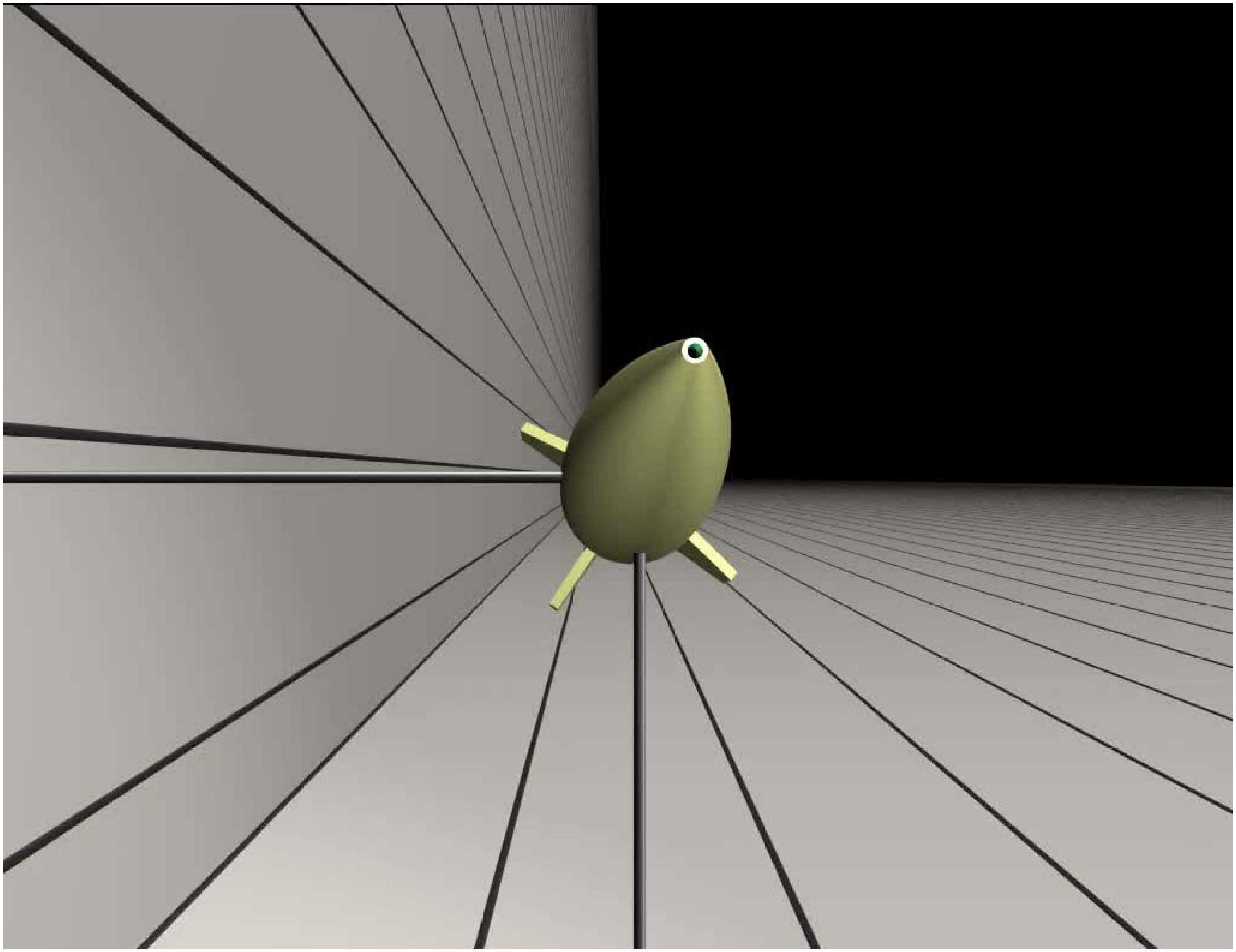
Motion Plot





Computed <u>orientations</u> (Euler angles) of the projectile match very well with the data measured in actual free flight tests.

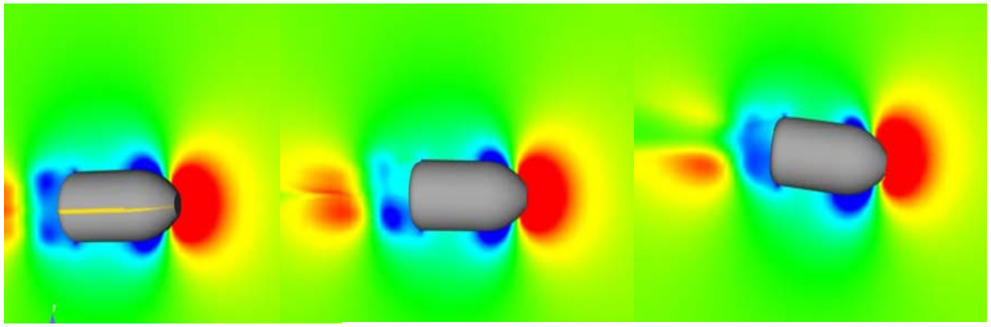
Virtual Fly-Out Visualization



Multidisciplinary CFD/RBD Fly-Outs

RESULTS

Spinning Projectile in subsonic flight



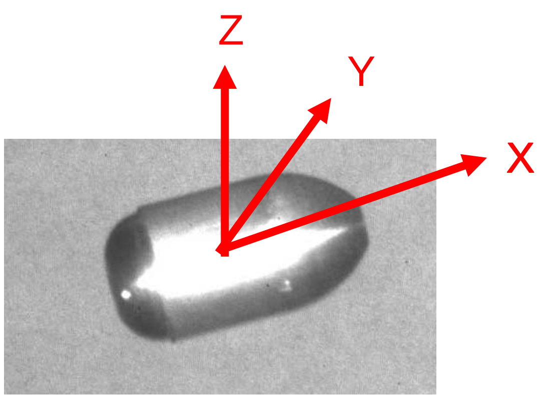
CFD/RBD COUPLING
Physical Properties and Initial Conditions

Mass Properties

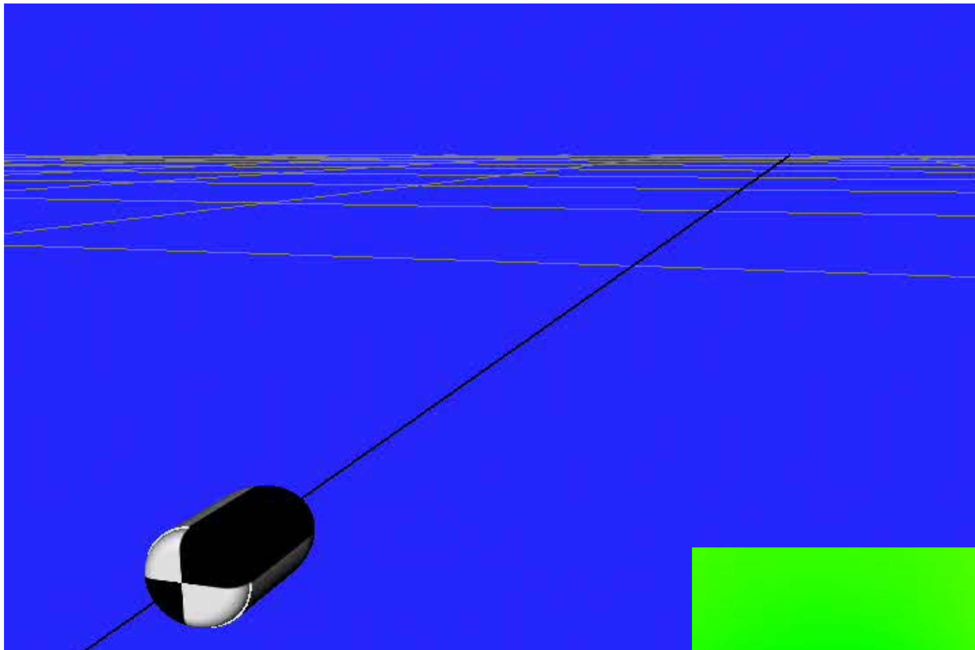
Shot Number	Projectile Diameter (mm)	Mass (kg)	Axial Inertia (kg- m2)	Inertia Y (kg- m2)	Length (mm)	CG (mm from nose)
22104	40.740	0.172	0.353E-04	0.816E-04	70.917	44.272

Initial Conditions at first station

Pitch [THETA] (rad):	-0.038
Pitch Rate [Q](rad/sec):	15.876
Yaw [PSI] (rad):	-0.117
Yaw Rate [R](rad/sec):	-12.315
Travel [X] (m):	4.549
Velocity-Missile [U] (m/sec):	130.697
Horizontal Motion [Y] (m):	0.193
Hor. Rate-Missile [V] (m/sec):	15.612
Vertical Motion [Z] (m):	0.116
Vertical Rate-Msle [W] (m/sec):	-2.235
Roll [PHI] (rad):	0.537
Roll Rate [P](rad/sec):	664.879



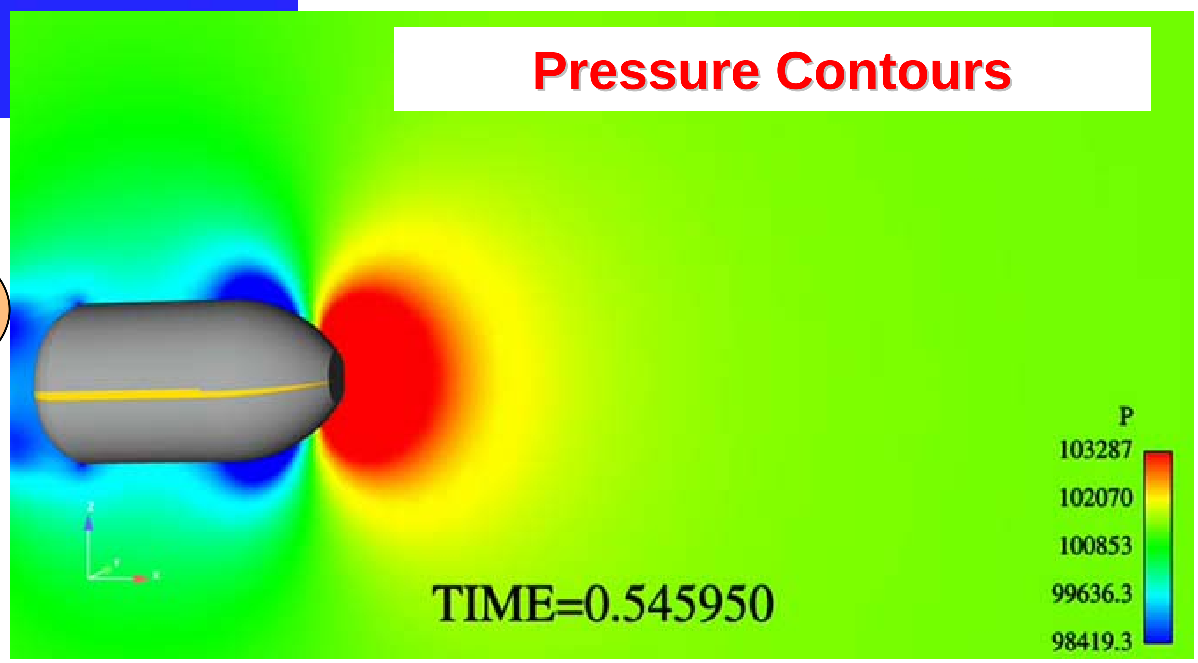
UNSTEADY AERODYNAMICS/FLIGHT DYNAMICS



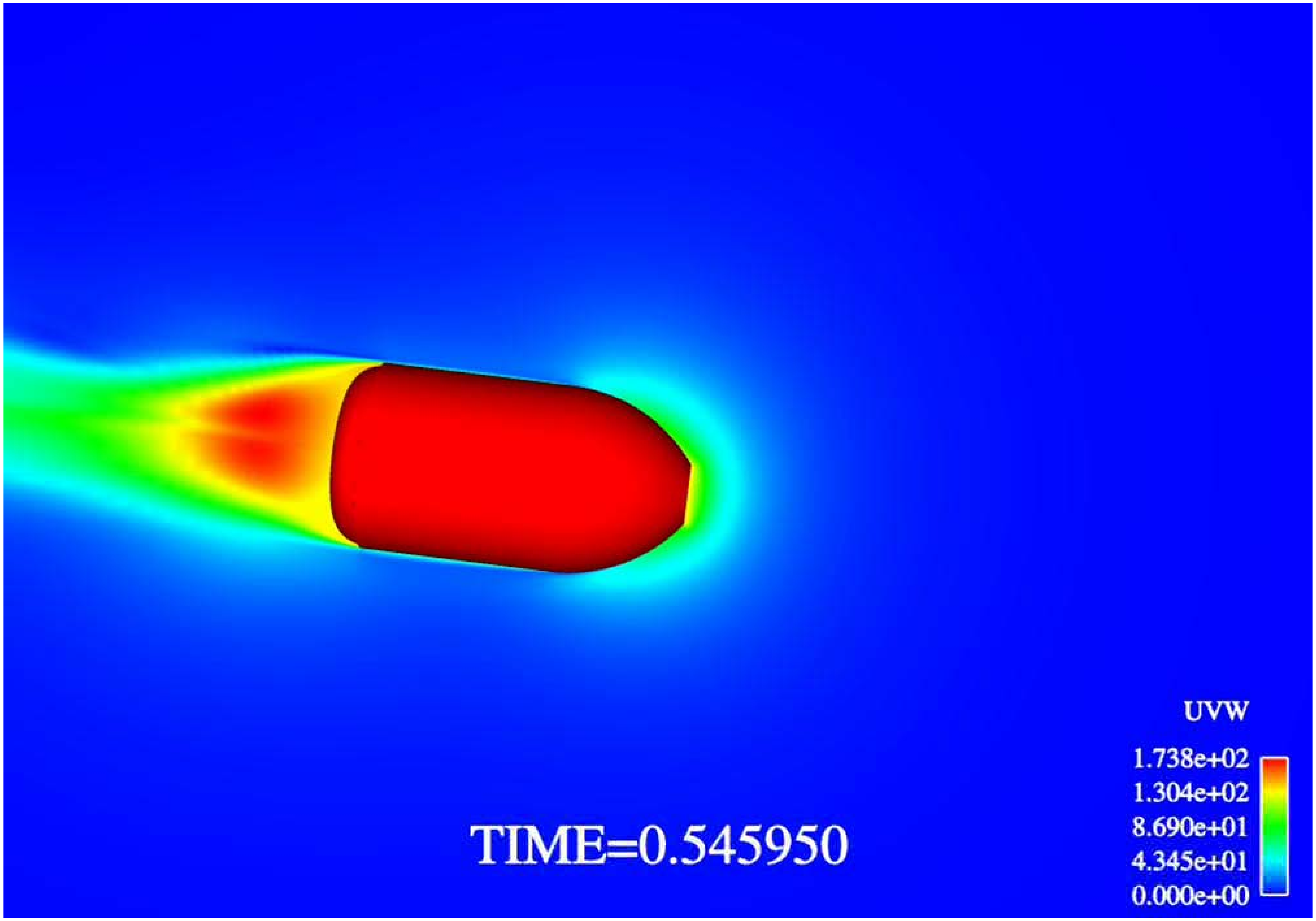
Coupled CFD/Rigid Body Dynamics (RBD) Simulations to compute the trajectory of in-flight spinning projectiles

Motion of a spinning projectile from the exit of the muzzle to the target

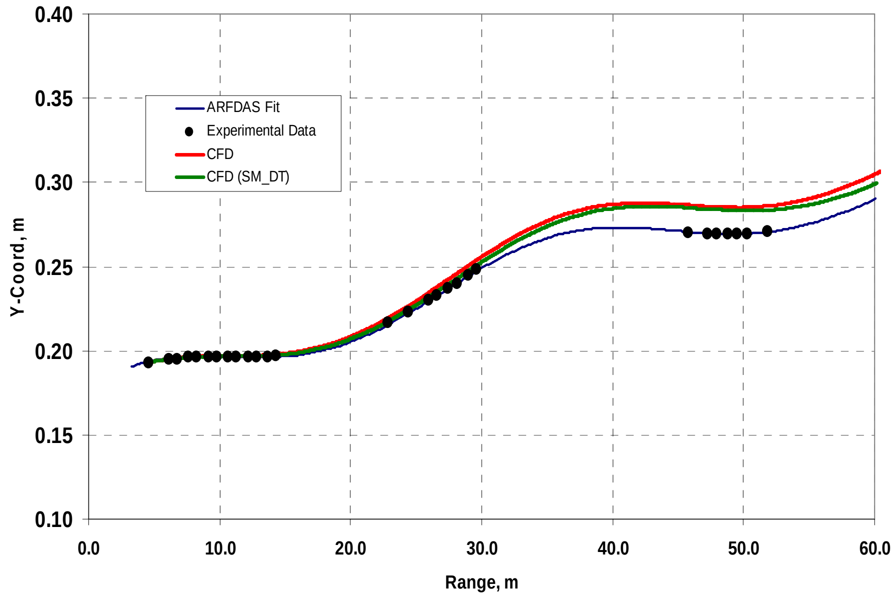
Initial Mach = 0.4



Computed Velocity Magnitude Contours
Initial Mach = 0.4

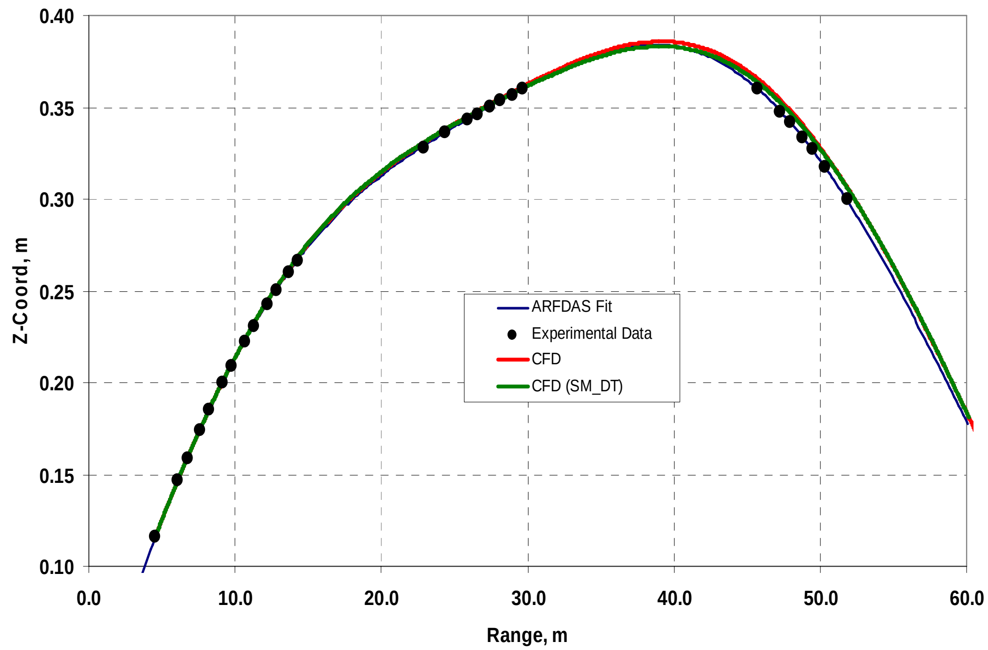


Computed Distances vs. Range

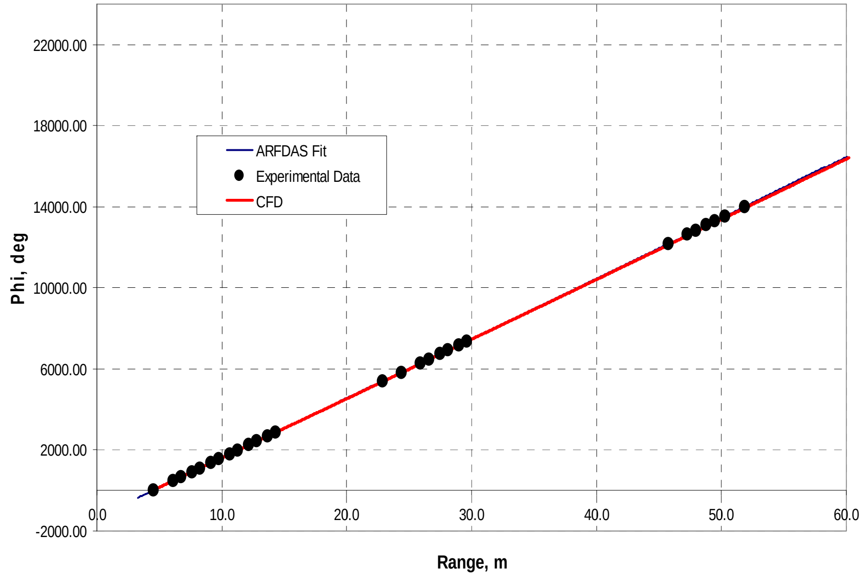


Y-distance

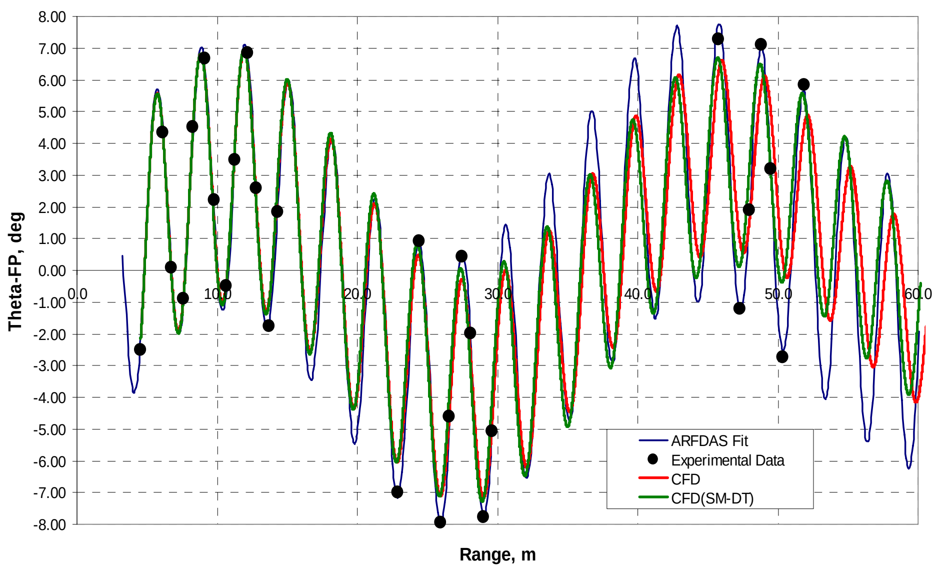
Z-distance

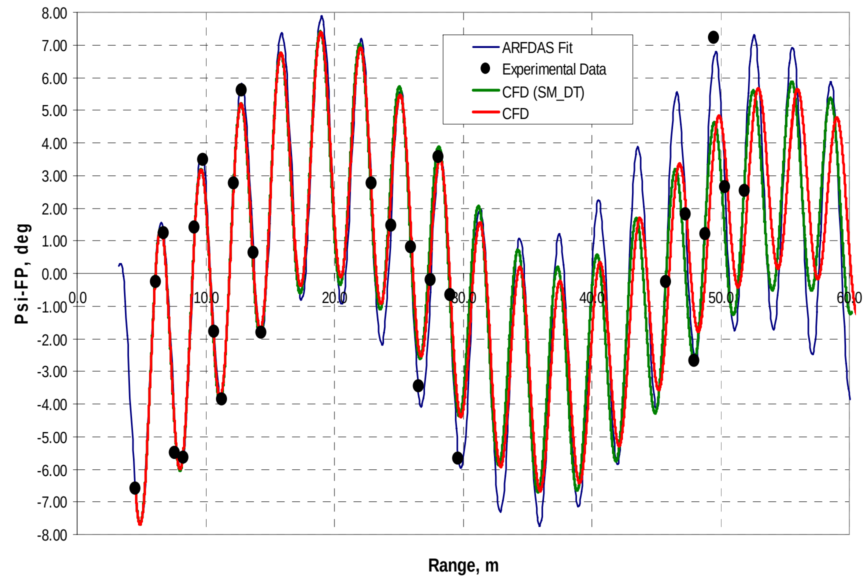


Comparisons of Computed Euler Angles

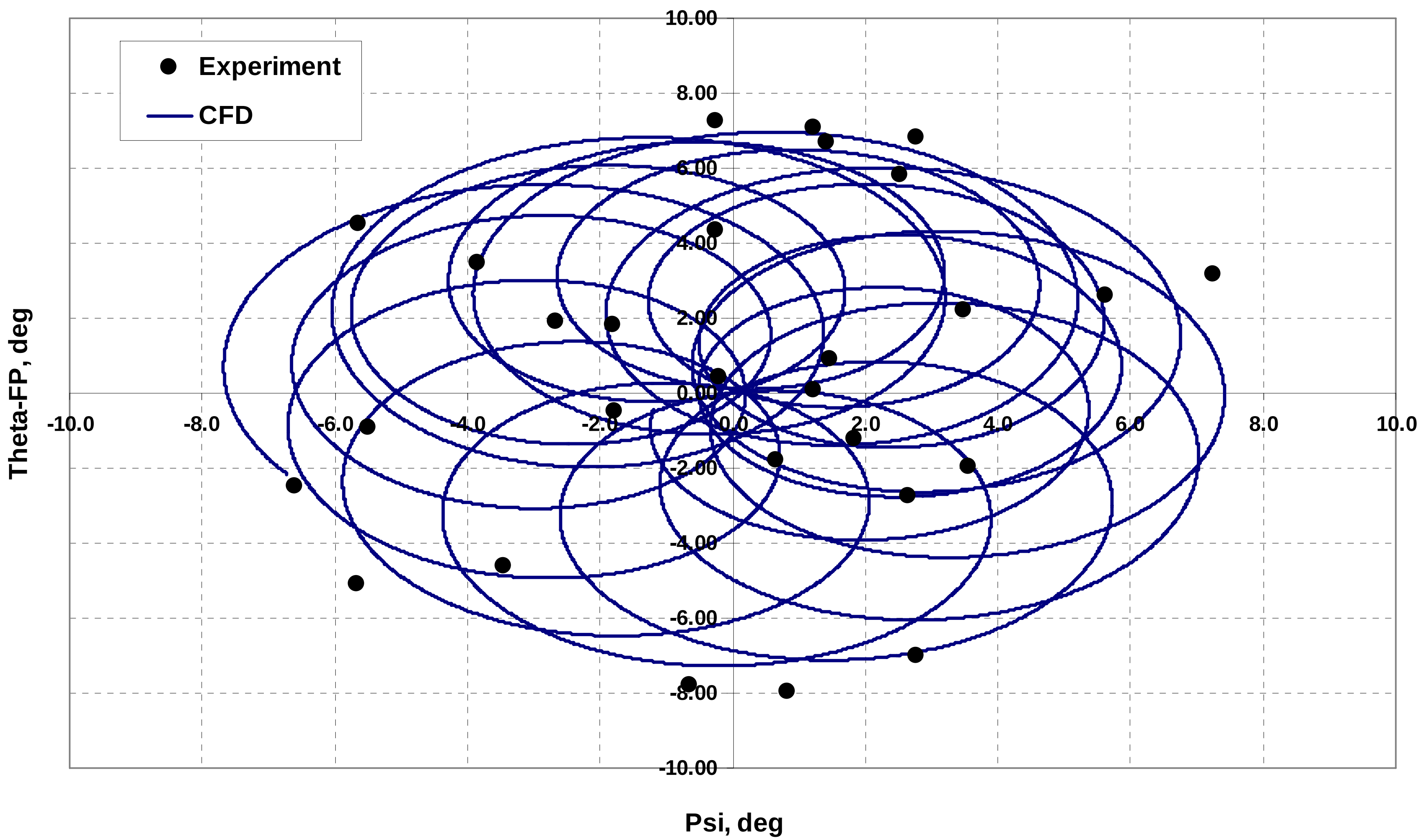


Computed <u>orientations</u> (Euler angles) of the projectile again match well with the data measured in actual free flight tests.



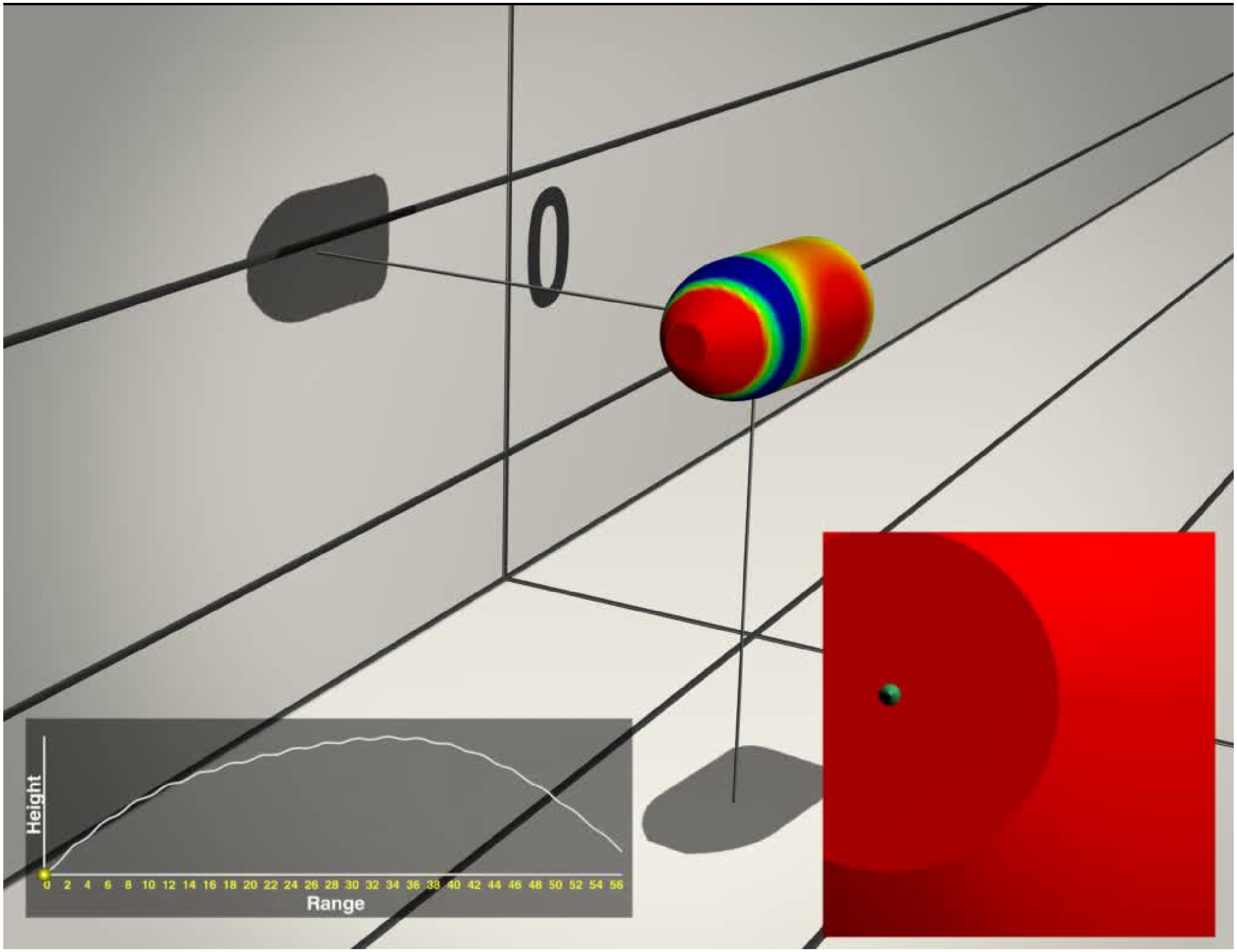


Motion Plot

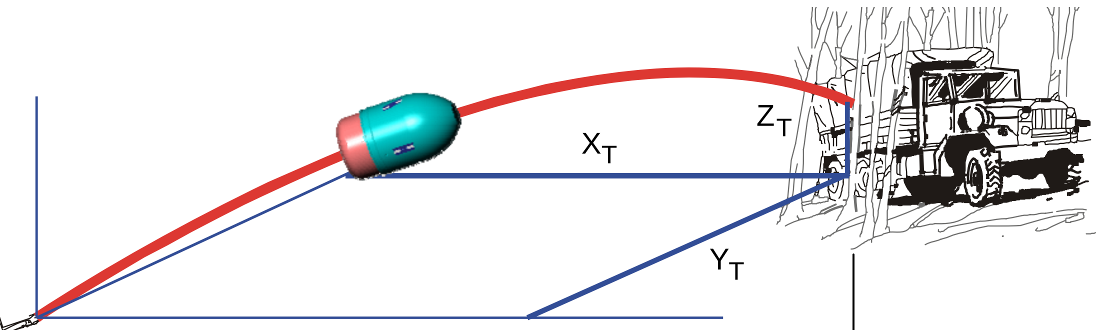


Experiment
CFD
Theta-FP, deg
Psi, deg
10.00
8.00
6.00
4.00
2.00
0.00
-2.00
-4.00
-6.00
-8.00
-10.00
-10.0
-8.0
-6.0
-4.0
-2.0
0.0
2.0
4.0
6.0
8.0
10.0

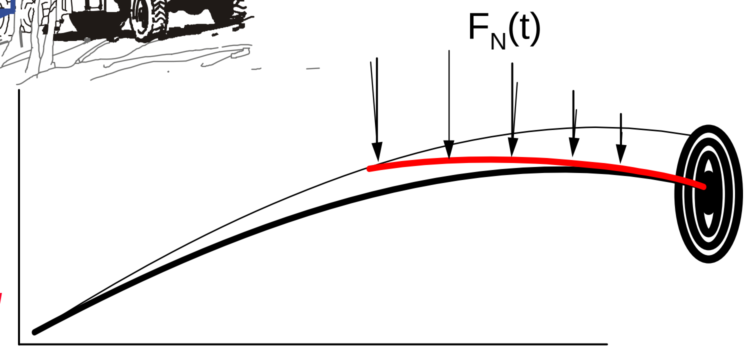
Virtual Fly-Out Visualization



Unsteady Aerodynamics with Flow Control



Demonstrate Adequate Aerodynamic Steering Forces using Flow Control



***Objective:* Provide fundamental understanding of the flow phenomena associated with micro-adaptive flow control and assess its effectiveness to provide adequate aerodynamic forces to divert or guide a projectile to its target**

Pacing Technologies:

- High performance computing
- Advanced visualization
- Unsteady aerodynamics

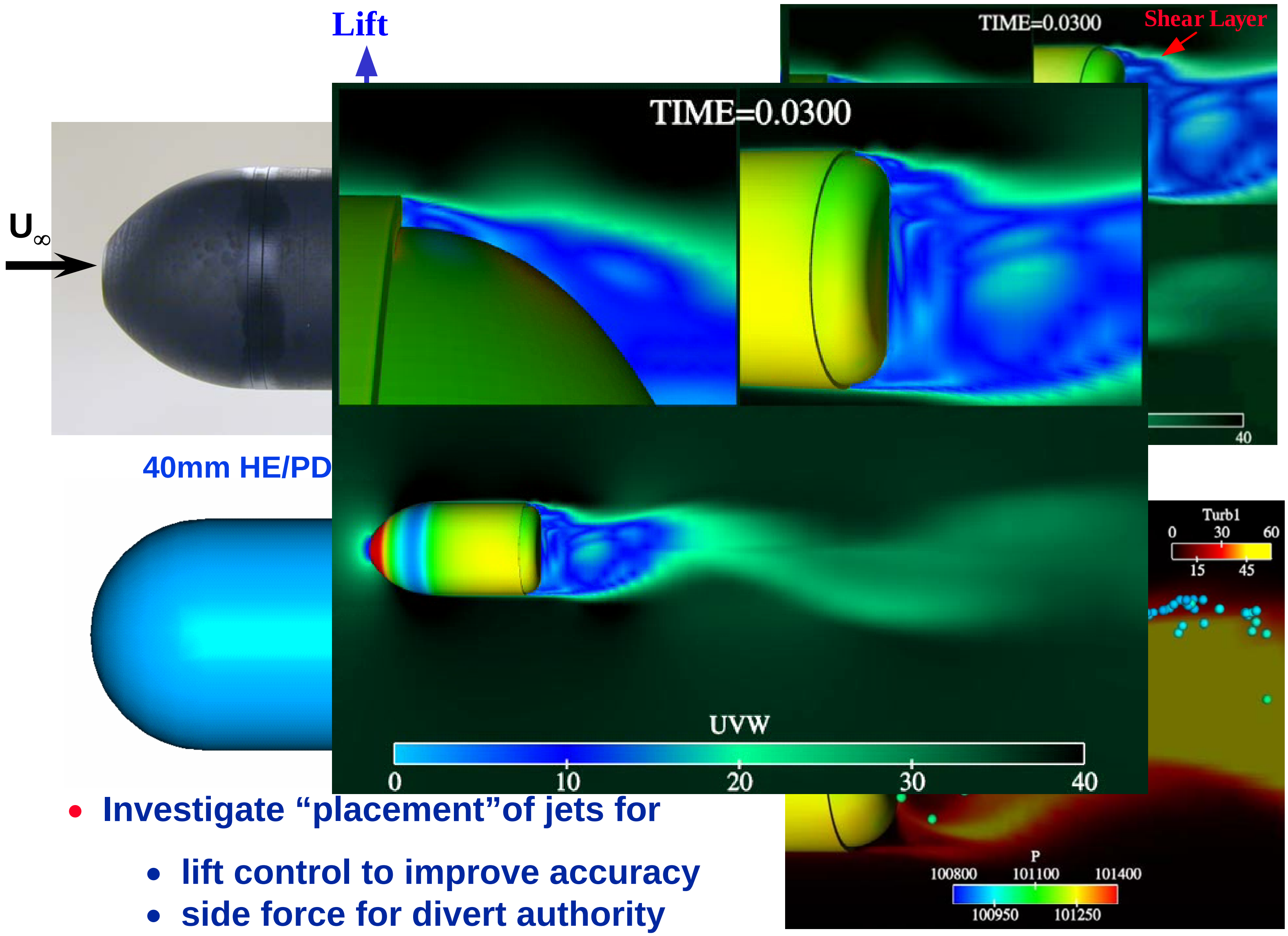
Warfighter Payoffs:

- Improved lift control
- Precision-guided munitions
- Increase lethality

High Fidelity Computational Tool for Improved Performance of Army Munitions

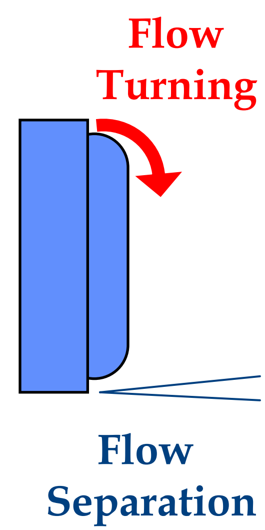
Micro-jet CFD Flow Visualization

U_∞ = 37 m/s, α = 0°, Ujet = 31 m/s, f= 1000 Hz



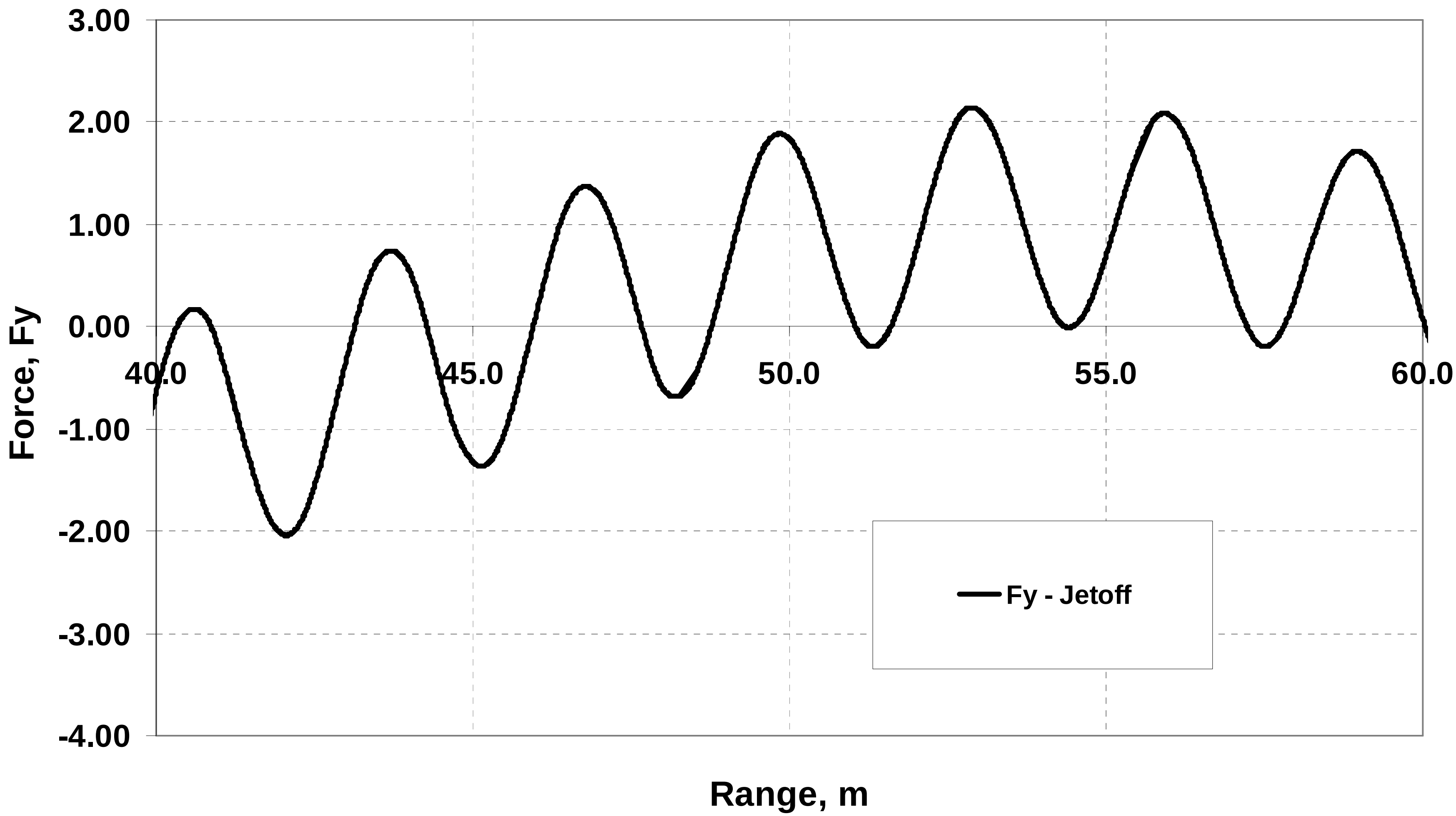
Jet-on all the time

Asymmetric Flow Separation

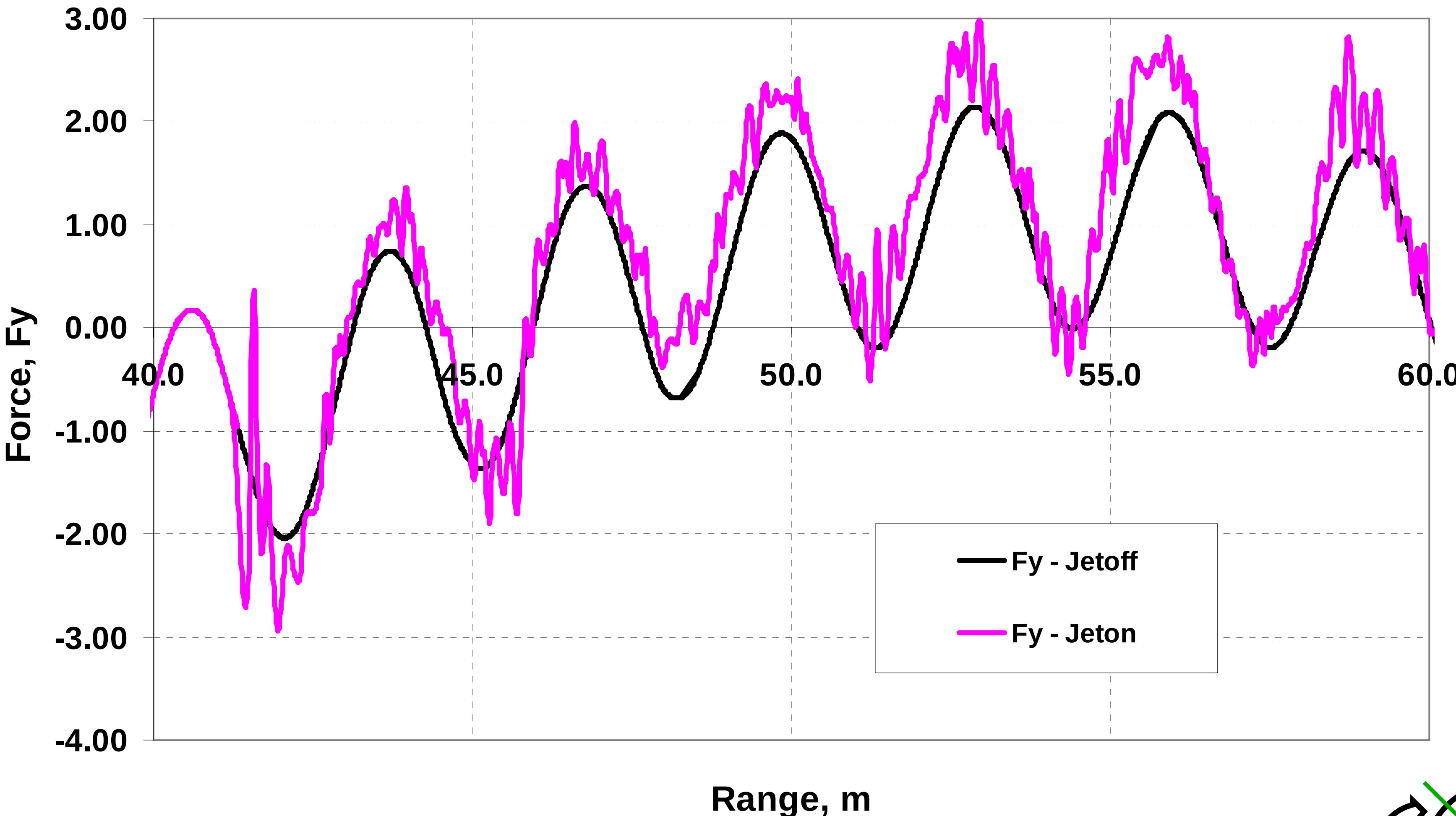


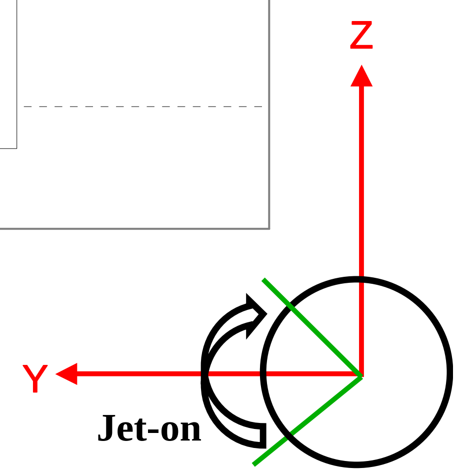
- Investigate "placement"of jets for
  - lift control to improve accuracy
  - side force for divert authority

Coupled CFD-6DOF Simulation Aerodynamic Force, Fy

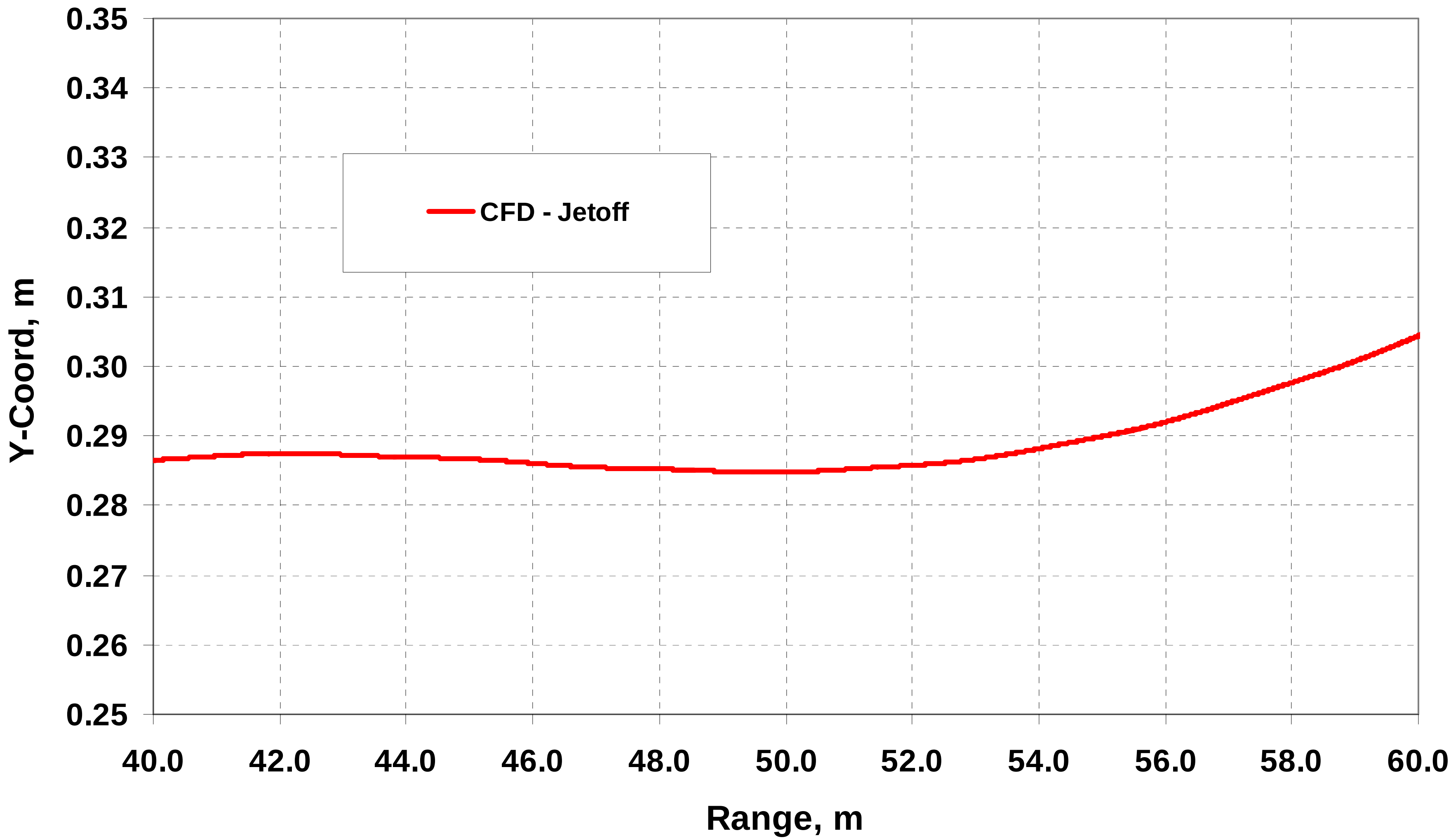


Coupled CFD-6DOF Simulation Aerodynamic Force, Fy

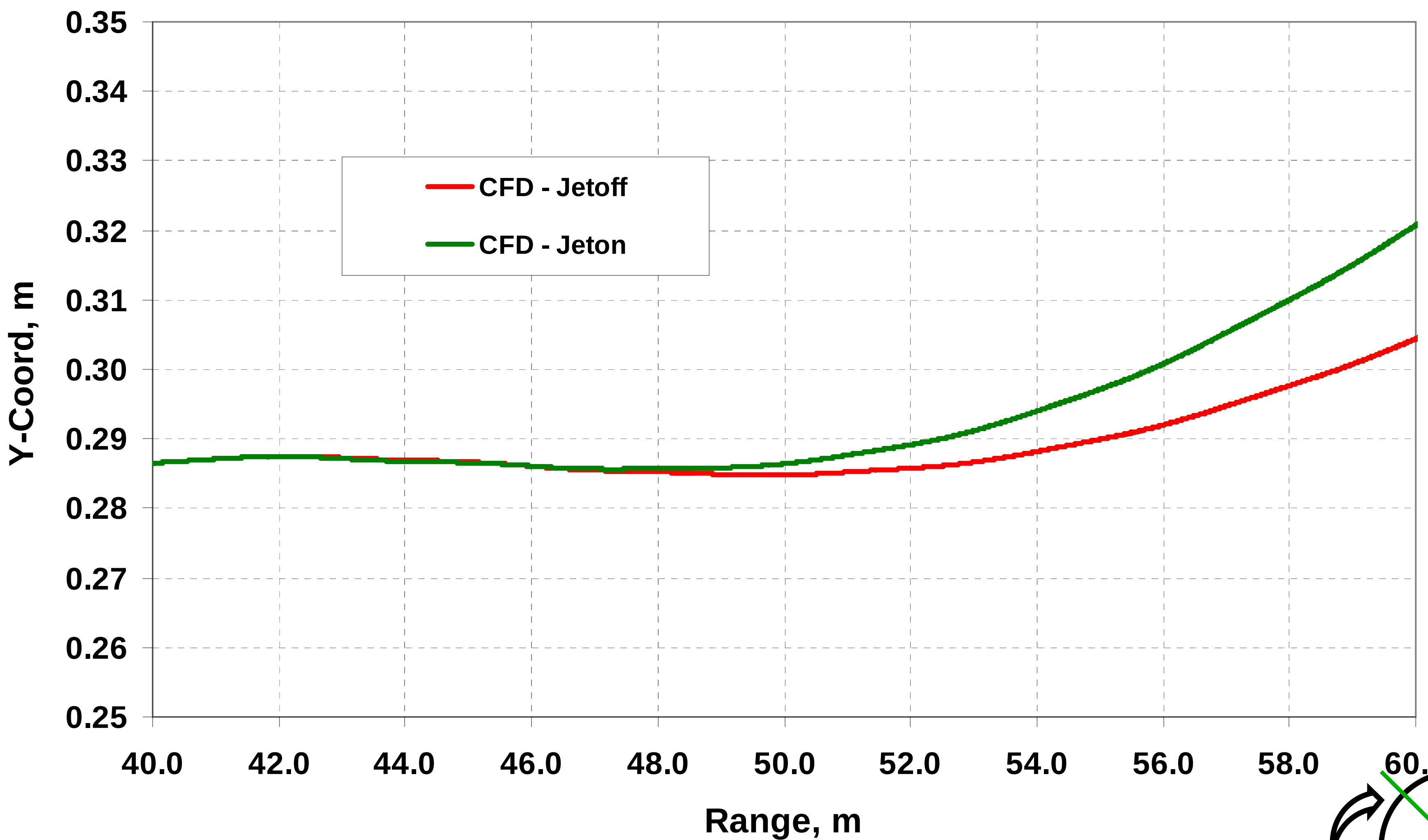


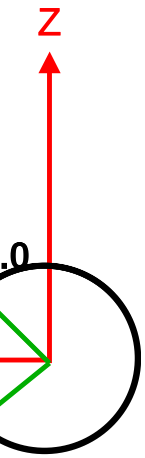


Coupled CFD-6DOF Simulation
Y vs. X



Coupled CFD-6DOF Simulation
Y vs. X

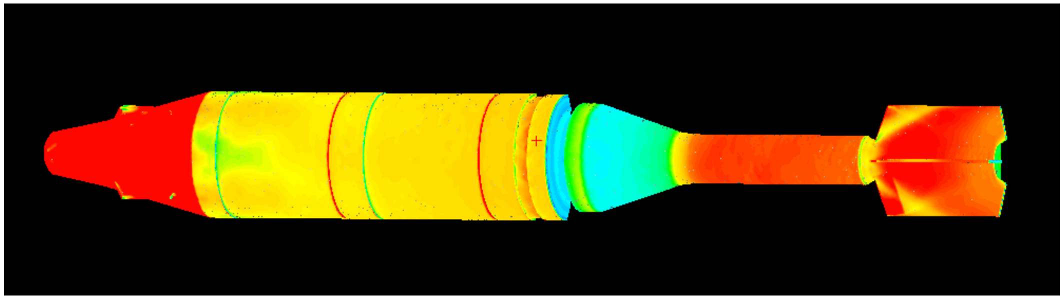


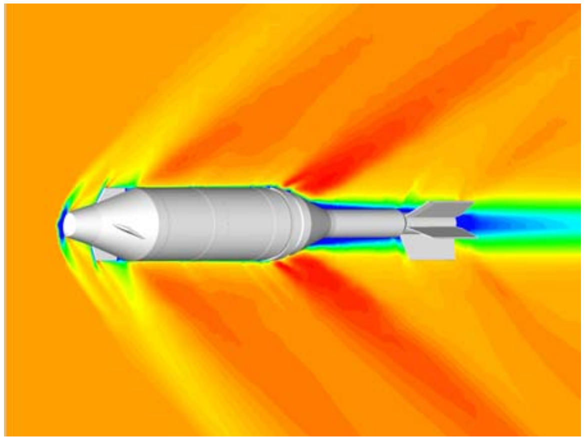


Maneuvering Projectile Aerodynamics with 6-DOF Fly-Out

RESULTS

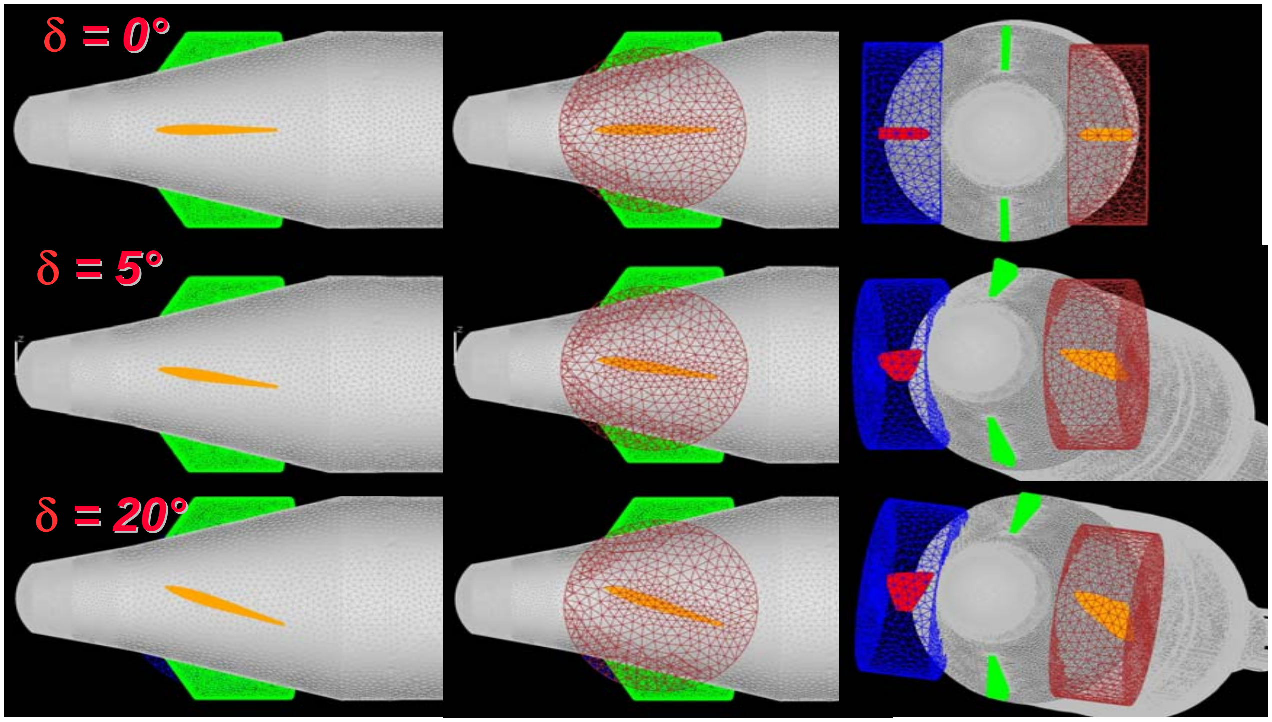
Canard-Controlled Projectile



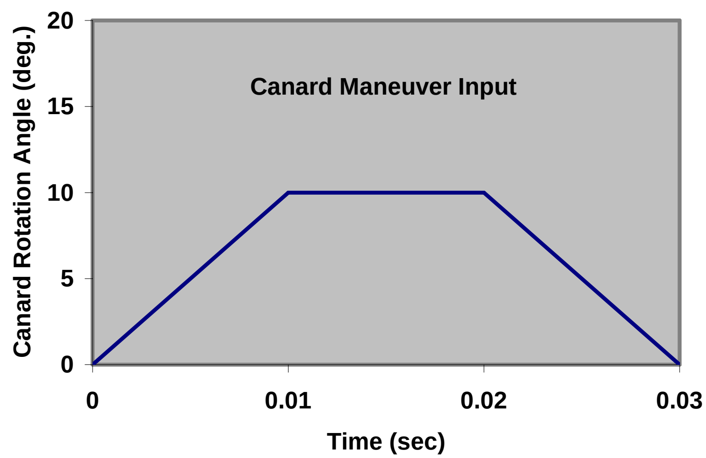


Canard-Controlled Projectile Aerodynamics

Dynamic Canard – Pitch Maneuvers

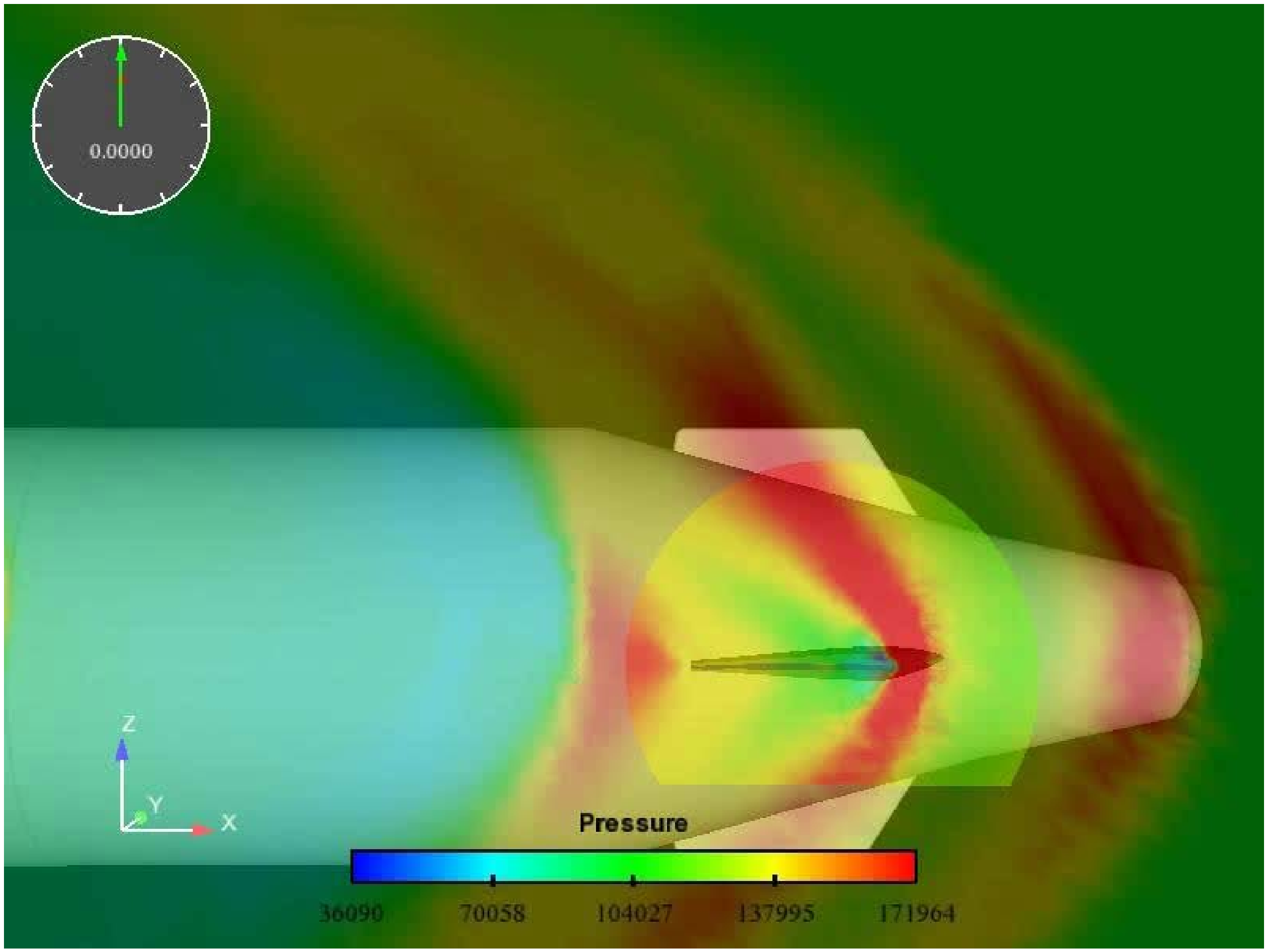


- **Canard pitch maneuver**
  - **Rotate the horizontal canards down δ = 10° in 0.01 sec**
  - **Hold the horizontal canards in that orientation for 0.01 sec**
  - **Rotate the horizontal canards back to δ = 0° in 0.01 sec**



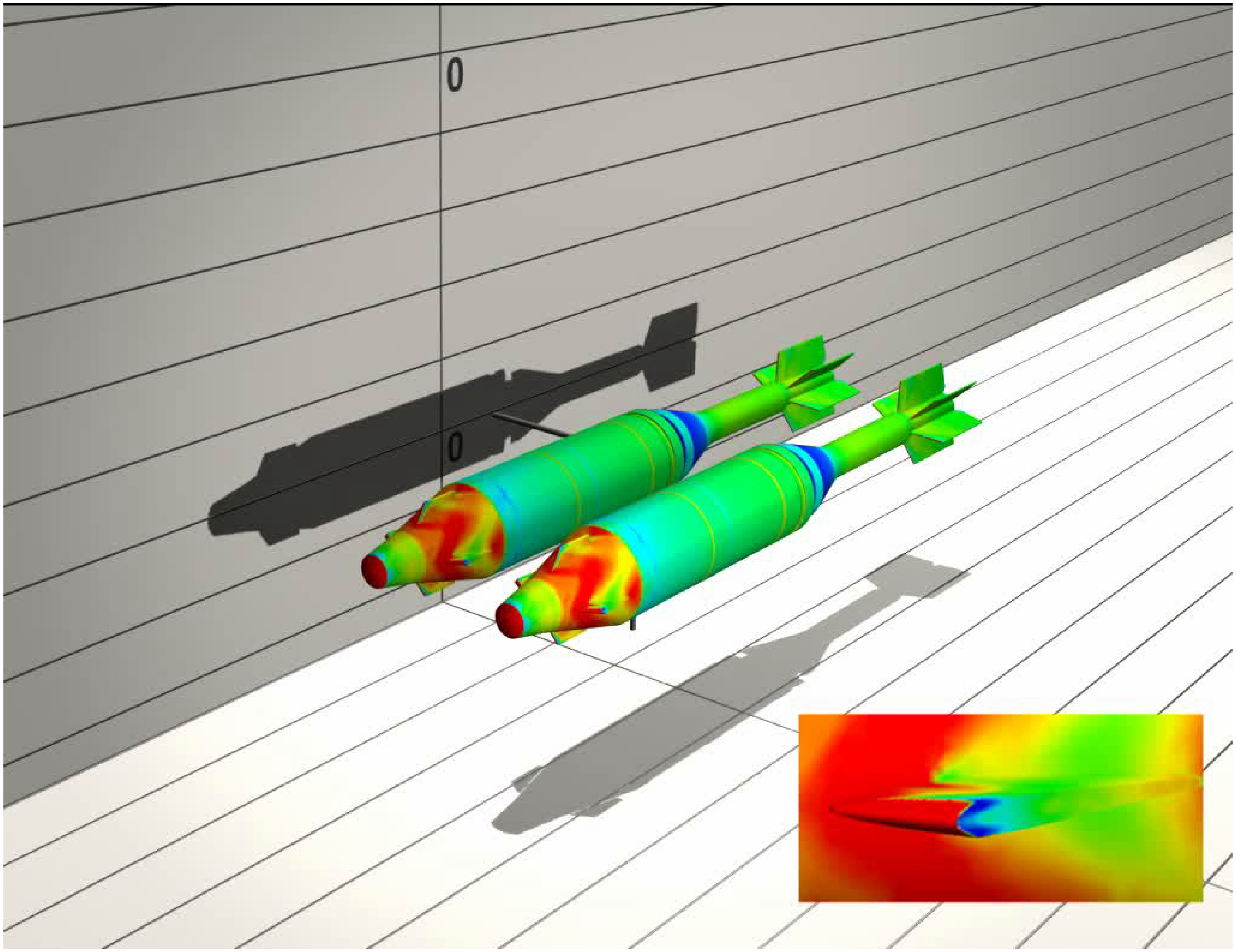
Computed Pressure Contours

Dynamic Canard – Pitch Maneuver (δ =10°)



Virtual Fly-Out Visualization

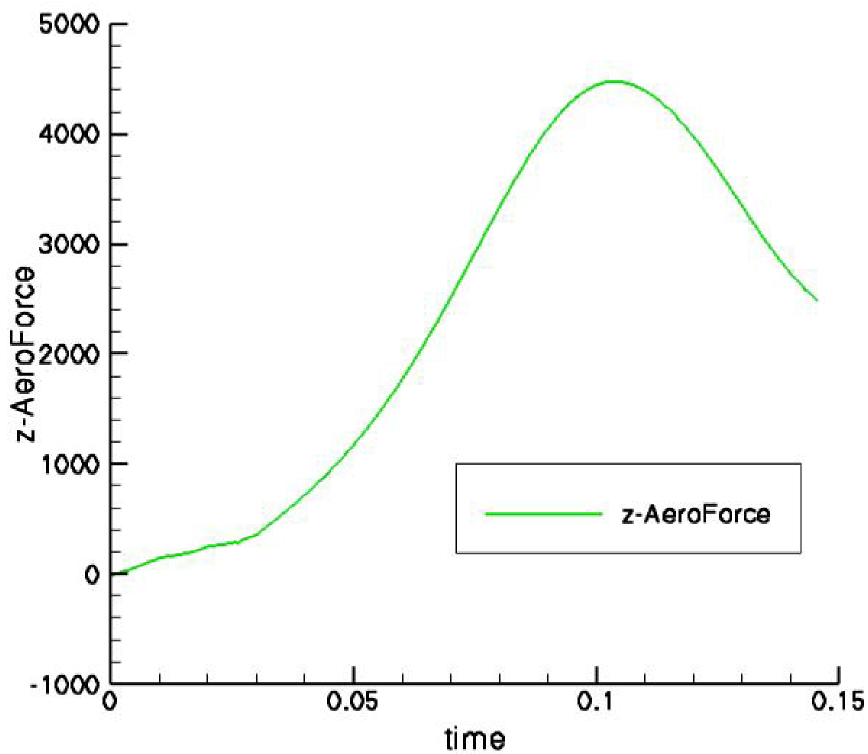
Dynamic Canard – Pitch Maneuver (δ =10°)



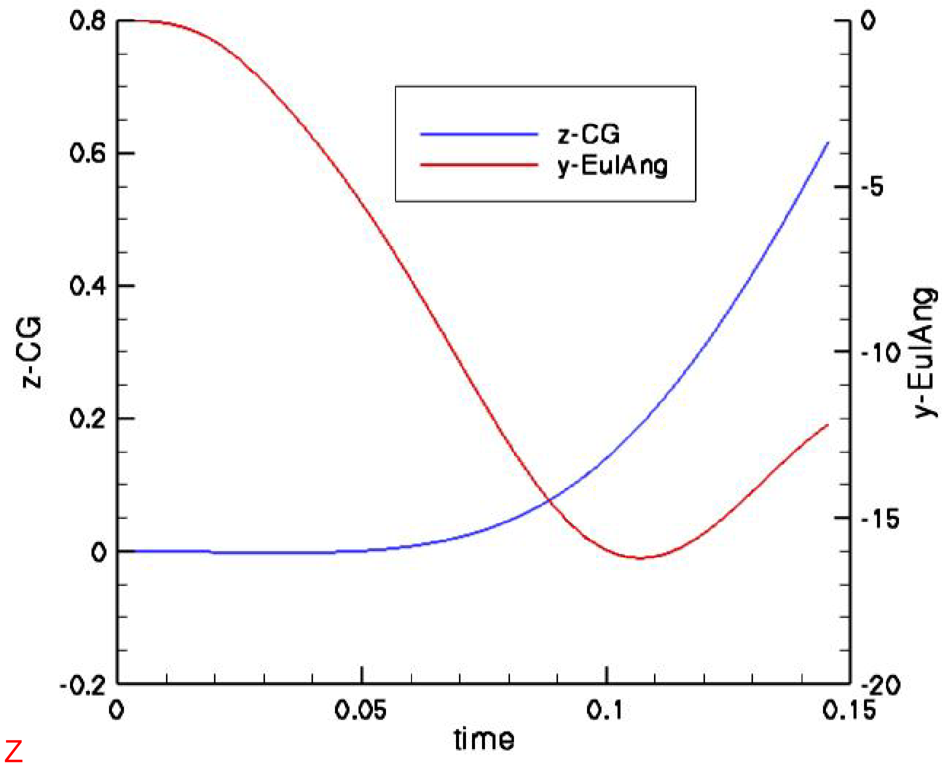
6-DOF Results

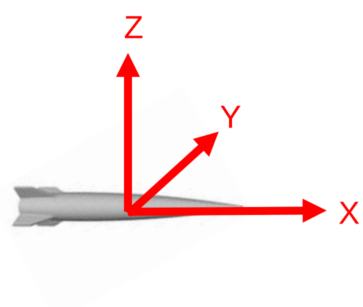
Dynamic Canard – Pitch Maneuver (δ =10°)

Lift Force



Z- distance (left); y-Euler Pitch Angle





y-EulAng = Pitch Angle (θ)

+ Nose down

Concluding Remarks

- Development and application of advanced CFD predictive technologies are critical for smart munitions aerodynamics
- Multidisciplinary CFD/Rigid Body Dynamics Coupling for Virtual Fly-Outs
  - A new way to determine the unsteady aerodynamics and flight dynamics in an integrated manner
  - Represents a significant increase in predictive capability
- Technologies developed in this research provided critical information such as the level of MAFC force, direction of divert, and unsteady aerodynamic effects required for design and control of spinning projectiles in flight
- Unsteady aerodynamics/flight dynamics for maneuvering munitions (fins/canards control)
  - Dynamic canard-control using unstructured Chimera
  - Pitch and Roll maneuvers

CURRENT AND FUTURE EFFORTS

- Continue development and validation of the CFD and CFD/6-DOF coupling techniques
- CFD/RBD/GN&C/Fluid-Structures Interaction
- Compute unsteady aerodynamics/flight dynamics for maneuvering munitions (fins/canards control)
- Applicable to many weapon development programs including small and medium caliber projectiles
- Reduce design cost -- simulate, simulate, test

- **Multidisciplinary coupled simulations and advanced HPC are key to the future weapon design and development programs of maneuvering munitions.**